UTILIZAREA UNOR MATERIALE COMPOZITE AVANSATE LA PROIECTAREA ȘI FABRICAREA UNOR PALETE DE ROTOR CENTRIFUGAL
CENTRIFUGAL ROTOR BLADE:DESIGN AND MANUFACTURING USING ADVANCED COMPOSITES

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Integration of advanced composite materials with polymeric matrix in aerospace domain (turbomachinery, aircraft structures, spacecraft, satellites) is an area of interest for many researchers, large integrators and manufacturers.

Polymeric composite materials can be defined as heterogeneous materials, obtained by associating, in a directed order, different components, one of them being a polymer.

In this paper the first technological stage in the development of a centrifugal compressor rotor is presented, starting from optimizing an existing version of the rotor considering the autoclave technology, developing the new rotor design, mould design and manufacturing and one blade manufacturing trials using advanced composites precursors - prepregs.

Three composite material precursors were evaluated and HexPlyM49/ 42%/200T2X2/CHS-3K was selected as final material to manufacture the compressor rotor. This decision was based on results obtaind by finite element analysis and experimental analysis. It consists in an epoxy resin reinforced with 3K high strength carbon fibers (3K-CHS), twill 2x2 fabric.

It was concluded that an entire rotor blade can be obtained using the technological process presented and advanced composite materials, however the autoclave technology will be used to manufacture the final compressor rotor.

Integrarea materialelor compozite avansate cu matrice polimerică în domeniul aerospațial (turbomașini, structuri ale avioanelor, navete spațiale, sateliți) este un domeniu de interes pentru mulți cercetători, mari companii integratoare și pentru producători. Materialele compozite polimerice pot fi definite ca materiale cu structură eterogenă, obținute prin asocierea într-o ordine dirijată a unor componenți diferiți, dintre care cel de bază este de natură polimerică.

În această lucrare este prezentată prima etapă tehnologică a dezvoltării unui rotor de compresor centrifugal, pornind de la optimizarea versiunii existente a rotorului având în vedere metoda de polimerizare în autoclavă, proiectarea noului rotor, proiectarea și fabricarea matriței și realizarea unei palete utilizând precursori ai materialelor compozite avansate – prepreg-uri.

Trei precursori ai materialelor compozite au fost evaluați și HexPlyM49/ 42%/200T2X2/CHS-3K a fost selectat ca material final pentru fabricarea rotorului de compresor. Această decizie a fost bazată pe rezultatele obținute în urma analizei cu elemente finite și analize experimentale. Materialul constă într-o matrice epoxidică care înglobează faza de ranforsare formată din fibre de carbon tip 3K cu rezistență ridicată (3K-CHS), țesatura twill 2x2.

S-a concluzionat că o paletă întreagă de rotor poate fi realizată utilizând procesul tehnologic prezentat, respectiv materiale compozite avansate, totuși metoda polimerizării în autoclavă va fi utilizată pentru fabricarea rotorului de compresor.

Keywords: *centrifugal rotor, composites, composite rotor, composite blade*

1. Introduction

All industrial fields are in a continuous development, thereby research projects are funded to increase products efficiency, reduce the manufacturing and maintenance costs of components and reduce pollution of the overall system. In the aerospace field, the researches are based on the same reasoning as other industrial sectors, thus a solution to multiple requirements is replacing conventional materials used in components manufacturing with advanced composite materials.

Ever since they were discovered, composites were integrated in aerospace applications, to manufacture different components and structures, like random, skins and fuselages, pressure vessels, fan blades and tubes for satellites [1]. In the last decade a great concern for the material science and aerospace engineers represented the increasing demand for composite rotating components that can reduce the noise in jet engines. Studies were conducted to design and test composite axial compressor blades with focus on vibration behavior and it was observed that composite materials can contribute to a reduction of vibration amplitudes due to their inherent advantageous damping behavior and their high specific stiffness [2].

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Most of research studies regarding rotary blade components were conducted on helicopter rotors or wind turbine rotors [3-6], especially due to the fact that the composites materials for this type of structures shall meet lower level requirements compared with heavy duty components like fan blades, axial/centrifugal blades or turbine blades.
However, even if high demands are imposed for this type of high speed rotors, researches were made to integrate composite materials in such applications. For example, the LEAP engine's fan blades are manufactured of 3D woven carbon fiber reinforced composites and they are currently used to fly commercial planes like Airbus A320neo, Boeing 737 MAX or COMAC C919 [7]. Also, a modern airplane, like Boeing 787 Dreamliner, consists of 50 % polymer composites, a fighter aircraft like the Eurofighter consists of 70% polymer composites. For instance, a wing made of polymer composites is assembled by the junction of 10 elements and a metal wing made of 100 elements. This means that construction of a metal wing costs more. Moreover, strength of CFRP is six to eight times higher than that of aluminum, and the same time, CFRP density is 1.5 times lower [8].
The goal of this research was to provide technological and material solutions to reduce the weight and to increase the performance of a centrifugal compressor rotor. A specific goal in this research was to develop and manufacture a centrifugal compressor rotor using advanced composite materials and autoclave technology. The central compressor manufacturing from composite materials is a complex task, and represents a new approach, both at national and international level, offering several advantages [9] which were highlighted above. The study started having as a reference the metallic centrifugal rotor of the CCAE
9-125 air compressor produced by Romanian Research and Development Institute for Gas Turbines COMOTI (Figure 1).
In this paper, the first technological stage in the development of the centrifugal compressor rotor is presented, starting from the design phase of the improved version using 3D CAD software, mould design and manufacturing, finite element analysis and experimental tests in order to select the optimum composite material selection and one blade manufacturing trials using advanced composites precursors.

2. Experimental

2.1. New centrifugal compressor rotor design

The first task of this research was to remodel the existing version of the CCAE 9-125 compressor rotor which comprises 17 blades with 3 mm blade thickness. Therefore, based on the numerical simulation calculus and the optimization iterations and 3D modelling using Solid Edge and

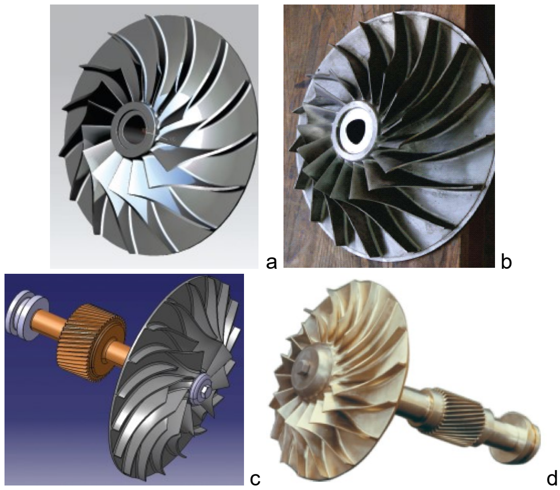

Fig. 1 - CCAE 9-125 centrifugal compressor rotor: a) rotor – CAD design; b) metallic rotor; c) rotor assembly stage I – CAD design; d) rotor assembly stage I / *Rotor pentru compresorul centrifugal CCAE 9-125: a) rotor – model CAD; b) rotor metalic; c) ansamblu rotor treapta I – model CAD; d) ansamblu rotor treapta I.*

CATIA software, an improved version of the compressor rotor was developed, considering the autoclave technology. This configuration presents a reduction in blades number (from 17 blades to only 7 blades) and a modification in the blade wall thickness. The new blade design has a 6 mm exterior wall thickness composed of 3 mm solid material and a 3 mm interior hollow passage. All geometries were obtained based on previous numerical simulations and existing versions, while the overall aerodynamic performances were not affected by the modifications.

In order to reduce the risks of the study and to achieve more experience, a 1:2.5 scaled mould for one blade impeller was designed and realized. The mould was manufactured from Necuron material and several preliminary tests were performed [10].

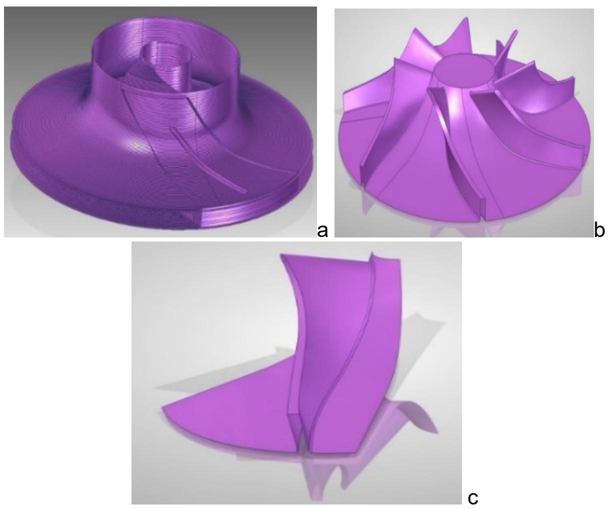

Fig. 2 - a) Remodeling Rotor surfaces; b) New version of centrifugal rotor surface; c) One blade surface / *a) Remodelarea suprafețelor rotorului; b) Noua versiune a suprafeței rotorului centrifugal; c) Suprafața unei palete.*

Figure 2 presents the new rotor configuration in 3 steps: a) the old rotor surface being remodeled, b) the new version of centrifugal rotor surface and c) shows the surface for a single blade.

2.2. Mould design and manufacturing

All 7 blade surfaces were extracted using CATIA and Solid Edge and were used to design the rotor mould.

The centrifugal rotor is a complex structure and for the manufacturing process of such structu-re, a multi-component mould was designed and manufactured. It consists of two main components, a base component (Figure 3 c) and a component to frame the blade geometry (Figure 3 b). These two main components were modelled and machined from an aluminum alloy (duralumin) block (Figure 4) to allow the manufacturing of each rotor blade. Also, a triplet (Figure 5a) was designed and fabricated to be used for each blade.

To manufacture each composite blade, the main component responsible for blade geometry was divided in 21 components consisting in 7 separators, 7 type 1 (pressure side) pieces and 7 type 2 pieces (suction side) (Figure 5).

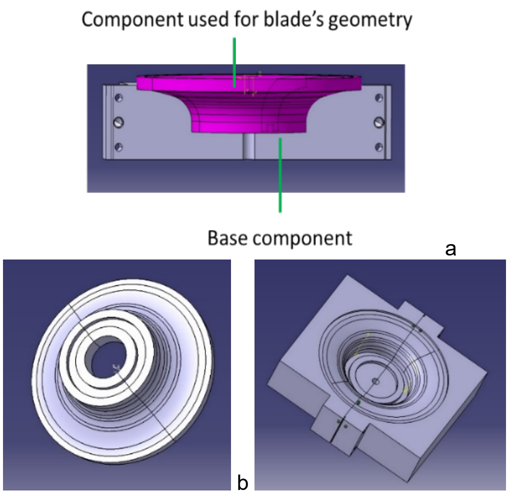

Fig. 3 - Mould components – 3D CAD model / *Componentele matriței – model 3D CAD.*

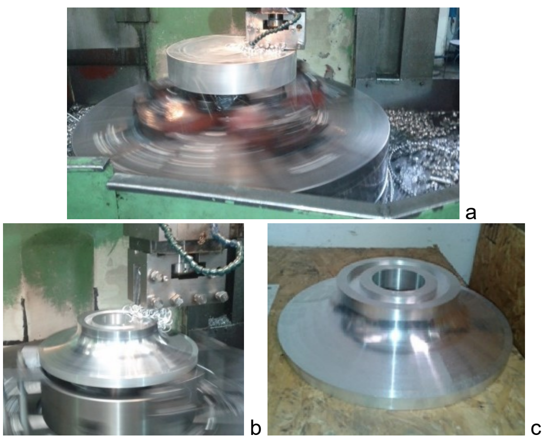

Fig. 4 - The machining process of the duralumin block / *Prelucrarea blocului de duraluminiu*

From the preform obtained, the type 1 and type 2 components were machined. An intermediary base component for one blade was

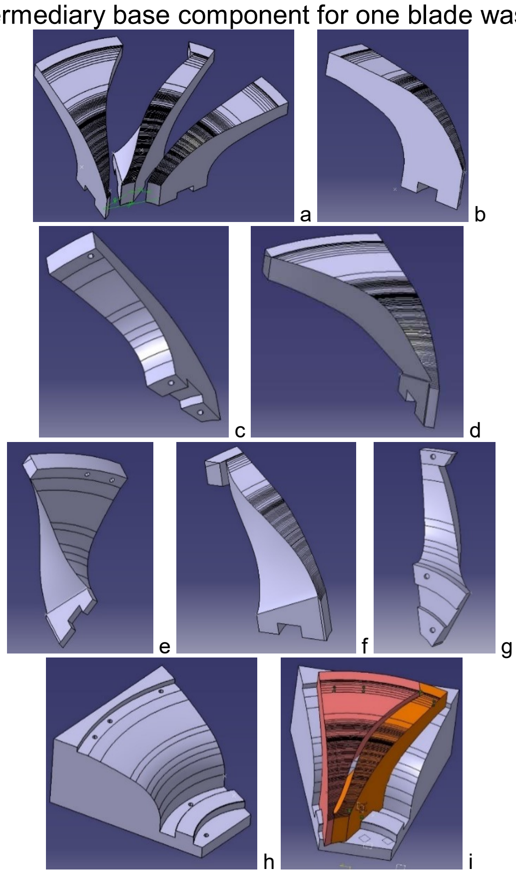

Fig. 5 - a) Triplet component used to form the geometry of one composite rotor blade; b, c) separator; d, e) type 1 component (intrados); f, g) type 2 component (extrados); h) base component for one blade; i) type 1 and type 2 components on the base components – CAD model – forming the final blade geometry */ a) Componenta triplet utilizată pentru fabricarea unei palete de rotor din material compozit; b, c) separator; d, e) componenta tip 1 (intrados); f, g) componenta tip 2 (extrados); h) componenta utilizată pentru baza unei palete; i) componentele tip 1 și tip 2 așezate peste baza – model CAD – obținerea geometriei finale a paletei*

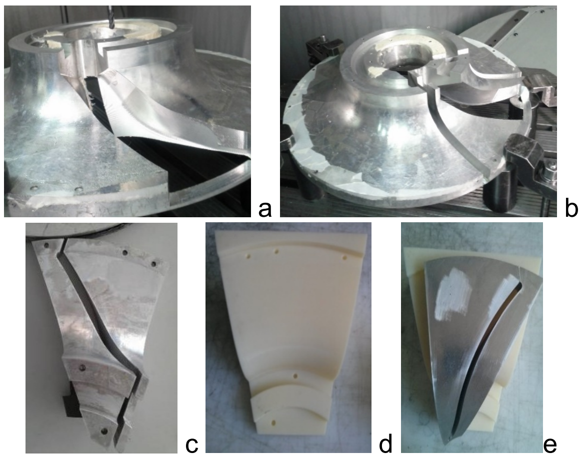

Fig. 6 - Triplet mould: a, b) The preform machining process; c) Type 1 and 2 metallic components; f) ABS base component; g) the triplet mould */ Matrița triplet: a, b) Prelucrarea semifabricatelor; c) Componentele metalice de tip 1 și 2; f) Componenta de bază din ABS; g) Matrița triplet.*

additive manufactured until the final pieces were finished, component which was used for the preliminary manufacturing trials.

A Dimension Elite 3D Printer with ABS was used to manufacture the base component. Figure 6 presents the machining process for type 1 and 2 components of the triplet and the final mould for one rotor blade.

2.3. Material selection and one rotor blade manufacturing

Three types of composite materials precursors – prepregs were evaluated. The first material selected was **HexPlyM49/42%/ 200T2X2/ CHS-3K** which consisted in a twill 2x2 high strength carbon fabric 3K impregnated with a toughened epoxy resin system (42% resin content) with good impact resistance and a glass transition temperature (Tg) of 120°C [11].

Another prepreg evaluated was **CC 370 ER450** – a 5 H satin high strength carbon fabric 6 K impregnated with a toughened epoxy resin system suitable for industrial applications and a maximium service temperature of 180°C [12,13].

The third prepreg used for technical trials was **CC 402 ER450** – a twill 2x2 high strength carbon fabric 6 K impregnated with the same toughened epoxy resin system as CC370 [14]. The woven carbon fibre fabrics are presented in Figure 7.

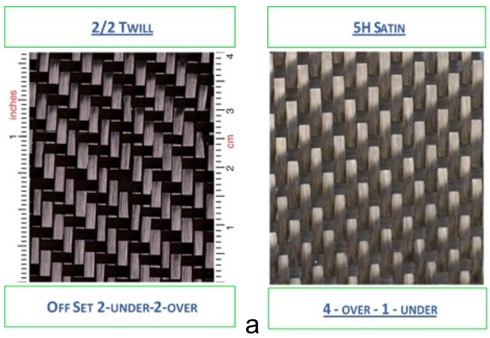

Fig. 7 – Woven carbon fabrics used for technical trials [15] / *Țesăturile din fibră de carbon utilizate pentru testele tehnologice.*

A finite element analysis (FEA) was realized in order to establish the load necessary for damaging the materials in case of tensile stress and shear stress. Two FEM models were realized using COSMOS/M software and element SHELL4L in case of tensile tests and SHELL3T in case of shear specimens. The input data for FEA were used the material characteristics from technical data sheets, and all material plies were laid up at 0°.

In Figure 8 can be observed the FEM models used for tensile test specimen, shear test specimen and Iosipescu device including the specimen.

To validate the results, experimental tests were performed using a universal testing machine Instron 8802 (load cell 250 kN) and consulting the standards SR EN ISO 527-4:2009 and ASTM D

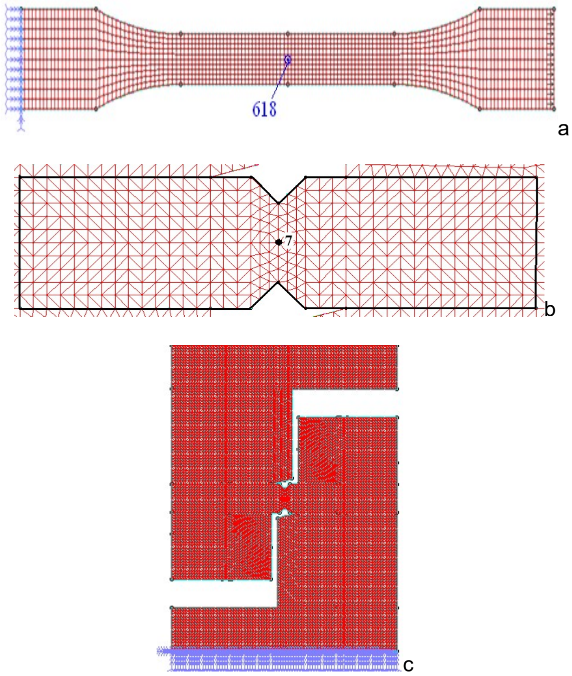

Fig. 8 – FEM models: a) specimen model for tensile test; b) specimen model for shear test; c) Iosipescu device and specimen for shear test / *Modele FEM: a) modelul epruvetei pentru încercarea la tracțiune; b) modelul epruvetei pentru încercarea la forfecare; c) dispozitiv Iosipescu cu epruveta pentru încercarea la forfecare.*

5379/1993. Figure 9 showes a specimen during the mechanical testing campaign.

Fig. 9 – Specimen during tensile test / *Epruvetă în timpul încercării la tracțiune.*

Technical trials were started by degreasing the mould components with acetone and afterwards a release agent (LOCTITE Frekote 770NC) was applied to facilitate the component removal after polymerization. To facilitate the component manufacturing, two different prepreg forms were realized and the curing of the first technological trials were performed in a vacuum assisted oven (POL-EKO model 240 SLN). Experimentally it was observed that 3 prepreg

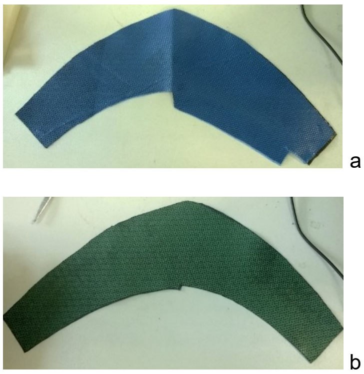

Fig. 10 - Prepreg forms used as models: a) type 1 prepreg form; b) type 2 prepreg form / *Șabloanele utilizate ca model pentru pliurile de prepreg: a) șablon pentru pliul de tip 1; b) șablon pentru pliul de tip 2.*

plies are enough to obtain the imposed thickness – one prepreg ply type 1 and two prepreg ply type 2 (Figure 10).

The prepreg plies were laid on the active surface of the mould, the lay-up of the first prepreg ply can be observed in Figure 11, and the following plies lay-up is presented in Figure 12.

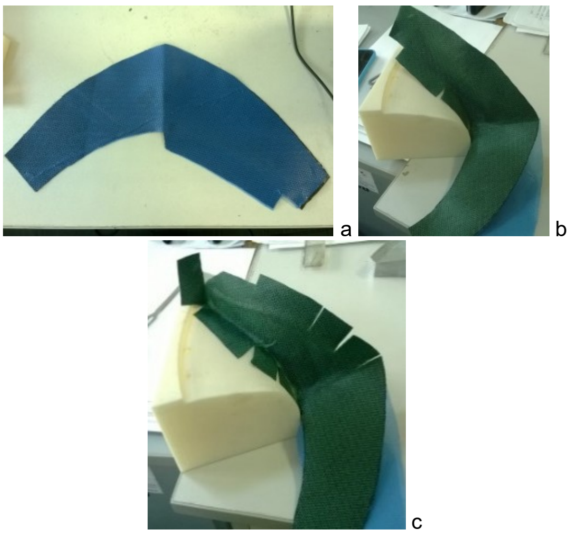

Fig. 11 - Lay-up of the first prepreg ply / *Așezarea primului pliu de prepreg.*

Fig. 12 - Lay-up of the second prepreg ply / *Așezarea celui de-al doilea pliu de prepreg.*

To prevent the internal bonding of prepreg plies, a release film was laid over them (Figure 13 a, b, c) and all the mould was wrapped in release film to prevent the breather bonding onto the mould.

Afterwards, a breather was placed all over the mould to protect the vacuum bag from the sharp metallic edges. The vacuum bag assembly was sealed with heat resistant tape and during vacuuming the bag was placed inside the mould's cavity to form the hollow passage of the blade.

Based on the prepreg data sheets and the temperature resistance of the ABS base component, a common curing cycle was selected, heating from room temperature until 82°C (heating rate of 2°C/min.), temperature holding for 5 hours and afterwards an oven assisted cooling step was added (Figure 14).

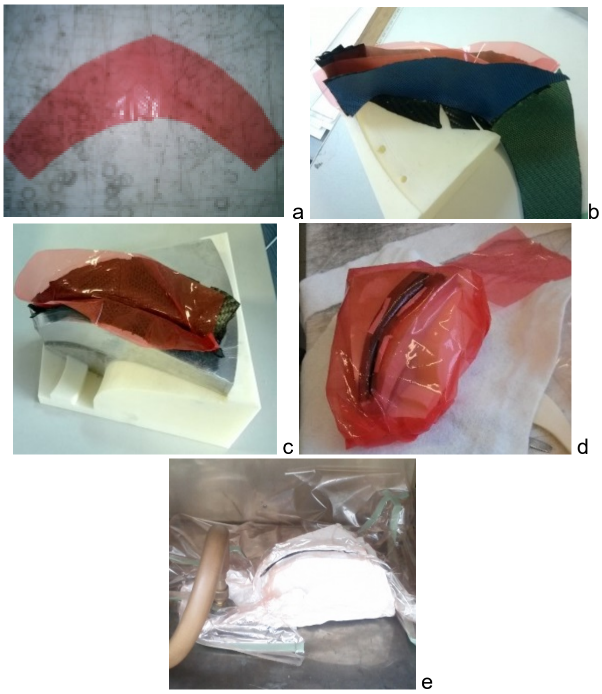

Fig. 13 - Mould closing and vacuum bag assembly: a) release film; b, c) release film integration between prepreg plies; d) the mould wrapped in release film; e) vacuum bag assembly / *Inchiderea matritei si realizarea sacului de vid: a) release film; b,c) integrarea stratului de release film între pliurile de prepreg; d) înfasurarea matriței în release film; e) sacul de vid.*

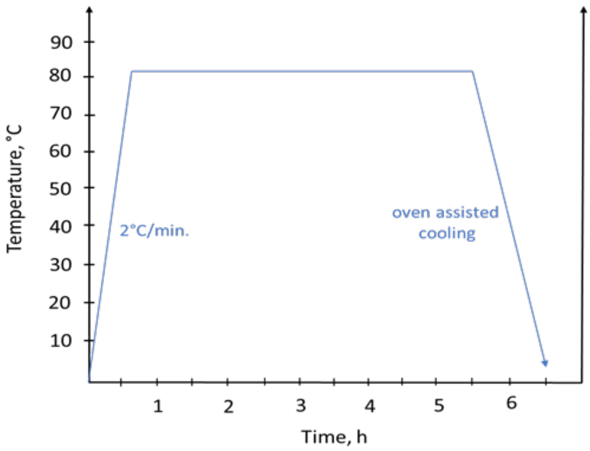

Fig. 14 – Curing cycle used for all prepregs / *Ciclul de polimerizare utilizat pentru toate prepreg-urile.*

3. Results and discussions

From FEA results it can be observed that HexPly M49 presents the highest performances in case of both tests (tensile and flexural). In case of tensile tests, the necessary loads in order to fracture the specimens were 21 kN in case of CC 370 ER 450 material, 25 kN in case of CC 402 ER 450, respective 29 kN in case of HexPly M49. Figure 15 shows the stress distribution in different material plies. Shear test simulation showed that the necessary load to rupture the specimen was 2615 N for CC 370 ER 450, 2774 for CC 402 ER 450 and 2909 for HexPly M49. Figure 16 presents the stress distribution in one material ply during shear test.

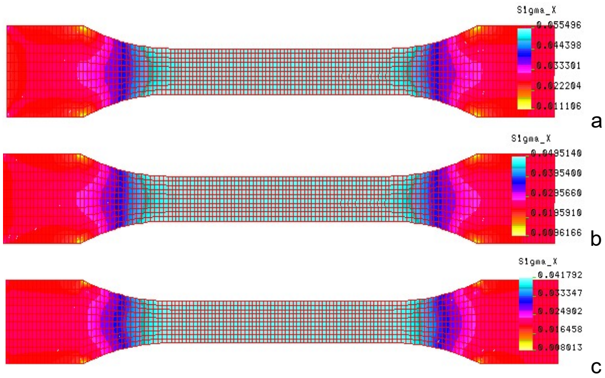

Fig. 15 – Stress distribution in one material ply in case of tensile test: a) for CC 370 ER 450; b) for CC 402 ER 450; c) HexPly M49 / *Distribuția tensiunii într-un pliu de material în cazul încercării la tracțiune: a) pentru materialul CC 370 ER 450; b) pentru materialul CC 402 ER 450; c) pentru materialul HexPly M49.*

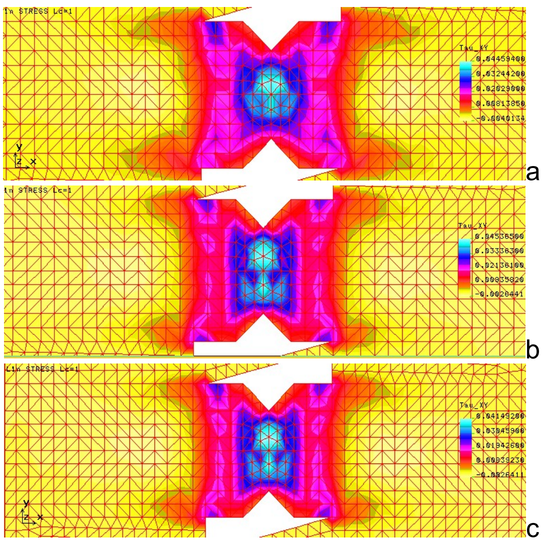

Fig. 16 – Stress distribution in one material ply in case of shear test: a) for CC 370 ER 450; b) for CC 402 ER 450; c) HexPly M49 / *Distribuția tensiunii într-un pliu de material în cazul încercării la forfecare: a) pentru materialul CC 370 ER 450; b) pentru materialul CC 402 ER 450; c) pentru materialul HexPly M49.*

It was confirmed that the best mechanical properties were obtained in case of tensile and shear stress on HexPly M49.Table 1 presents the average results obtained during testing campaign.

Table 1

Average values obtained in case of studied materials
Rezultate medii obținute în cazul materialelor studiate

Material	Test	Strength [MPa]	Load [N]
CC 370 ER 450	Tensile	1453	4289
	Shear	249	8511
CC 402 ER 450	Tensile	580	42891
	Shear	287	10163
HexPly M49	Tensile	907	66862
	Shear	312	12013

After the curing cycle was finished, the mould components were disassembled and the rotor blades were removed from the mould. It was observed that all three types of blades were easy to remove from the mould active surfaces. In all three cases, the interior hollow passage was formed due to the vacuum pressure applied inside the mould and the exterior geometry of the blades were formed according to the design. Figure 17 presents the rotor blades obtained after the curing cycle.

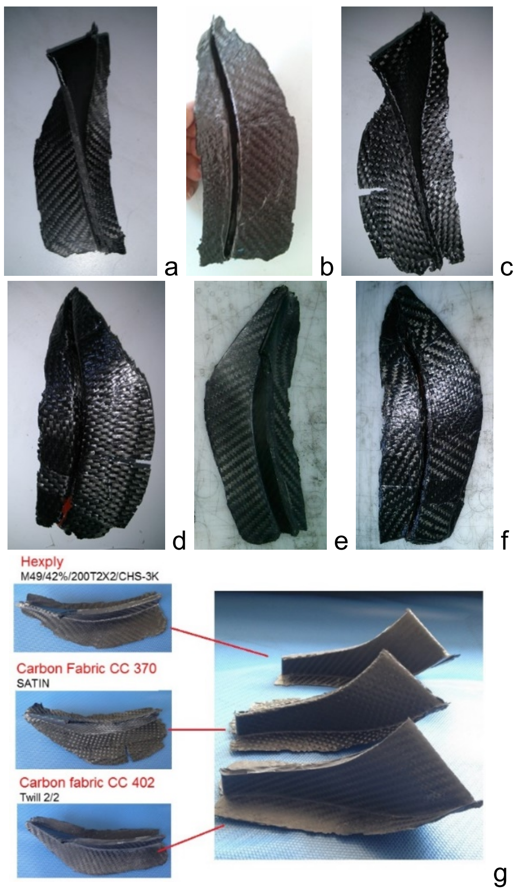

Fig. 17 - Rotor blades 1:1 scale - technological trials: a, b) HexPly M49 blade; c, d) CC370 blade; e, f) CC402 blade; g) all three rotor blades / *Paletele de rotor scara 1:1 – teste tehnologice: a, b) Paleta din HexPly M49; c. d) Paleta din CC370; e, f) Paleta din CC402; g) Cele trei palete de rotor.*

Regarding the integrity of the structure, it was observed that in case of HexPly and CC402 blade, the fabric was completely impregnated by the resin flow, but the CC370 blade presented multiple areas where the resin didn't completely impregnate the fabric. This could be a result of the insufficient resin content or due to the dense satin fabric. It resulted in delaminated areas which are undesired. CC370 material could be used in simpler structural geometries, but for this type of complex structure the CC370 is not a solution.

For the final structure the HexPly M49 pre – preg was selected based on FEA results, mechanical test results and preliminary technical trials. Also, it was established that for the final compressor rotor manufacturing process an autoclave will be used due to the fact that denser structures can be obtained using this technology compared with vacuum assisted oven method. Void free complex structures could be obtained by applying external pressure, not only the vacuum pressure, this resulting in high performance components.

4. Conclusions

The paper presents the first technical trials to manufacture one compressor rotor blade, a preliminary step during the manufacturing of a centrifugal rotor using advanced polymeric composites. The research started by improving an existing metallic reference of the rotor. The result of this task was a new design version of the centrifugal rotor which was composed of 7 blades (compared with the initial 17 blades) with 6 mm exterior wall thickness composed of 3 mm solid material and a 3 mm interior hollow passage (compared with initial 3 mm blade thickness).

Based on the 3D CAD model of the rotor, a mould was designed and manufactured.

Three composite material precursors were evaluated, HexPlyM49/ 42%/200T2X2/CHS-3K, CC 370 ER450 and CC 402 ER450 prepregs.

FEA was realised using the material characteristics from the technical data sheets, and they were validated by an experimental testing campaign. It was concluded that HexPlyM49/ 42%/200T2X2/CHS-3K presented the highest performances.

Preliminary technical trials were performed on one rotor blade sector to determine the plies sequence and to evaluate how the composite material precursors behave when complex shapes are formed.

The entire manufacturing process stages in case of one blade manufacturing were presented in the paper. Regarding the material selection, HexPlyM49/42%/ 200 T2X2/ CHS-3K prepreg was selected for the final structure based on the results obtained from FEA, mechanical tests and during technological trials. One of the main factors that influenced the selection of the proper material was the resin capability to impregnate the fibers and the capacity of the fabric to lay on complex shapes (as the compressor blade). Also, it presents a high mechanical resistance provided by the carbon fabric and adequate temperature resistance.

It was concluded that an entire rotor blade can be obtained using the technological process presented. During technical trials a vacuum assisted oven was used as curing method, but for the final compressor rotor an autoclave will be used to obtain a void free structure with high performances.

Acknowledgements

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