Manufacturing Aerospace Components using Bionic Technology

C. Sandu, S. Vintilă, M. Sima, F. Zavodnic, T. Tipa and C. Olariu

Abstract — The rule of thumb in aerospace industry is that lighter is better. Light composite materials have been used in aircraft and turbofan manufacturing for decades, due to their high strength and low density carbon fiber epoxy composite ~1.5(g/cm^3) compared with the lightest metallic alloy such as magnesium alloys ~1.8(g/cm^3). Nowadays, carbon fiber epoxy composites technology reached a top level in manufacturing fan blades for ultra-high bypass turbofans, but there is still room for improvement by reducing average density of composite components. This paper shows that using bionic technology resembling the structure of a bird bone to manufacture very light fan blades, fan vanes and fan housings is possible, having average densities several times smaller than the most advanced composites materials. This manufacturing technology could lead to very light propulsion systems like turbofans or propfans .

Keywords — fan blade, aircraft components, ultra-high bypass turbofan, bionic technology, carbon fiber epoxy composites

I. INTRODUCTION

Turbofan engines are today's most widely spread propulsion system that powers passenger aircrafts. These propulsion systems have at its core a turbojet engine equipped with a large diameter fan which produces thrust by accelerating atmospheric air. At first, the fan blades were made out of a single solid piece of steel or out of titanium as separated parts (Fig. 1) or from the same block of material together with the disc named *blisk* (Fig. 2) [1].

Constantin Sandu is with the Romanian National Research and Development Institute for Gas Turbines, Bd. Iuliu Maniu 220D, Bucharest, Romania (corresponding author phone: +40 0723 147 322; e-mail: constantin.sandu@comoti.ro).

Sebastian Vintilă is with the Romanian National Research and Development Institute for Gas Turbines, Bd. Iuliu Maniu 220D, Bucharest, Romania. (e-mail: sebastian.vintila@comoti.ro).

Mihail Sima is with the Romanian National Research and Development Institute for Gas Turbines, Bd. Iuliu Maniu 220D, Bucharest, Romania. (e-mail: mihail.sima@comoti.ro).

Felix Zavodnic is with the Romanian National Research and Development Institute for Gas Turbines, Bd. Iuliu Maniu 220D, Bucharest, Romania. (e-mail: felix.zavodnic@comoti.ro).

Traian Tipa is with the Romanian National Research and Development Institute for Gas Turbines, Bd. Iuliu Maniu 220D, Bucharest, Romania. (e-mail: traian.tipa@comoti.ro).

Cristian Olariu is with the Romanian National Research and Development Institute for Gas Turbines, Bd. Iuliu Maniu 220D, Bucharest, Romania. (e-mail: cristian.olariu@comoti.ro).

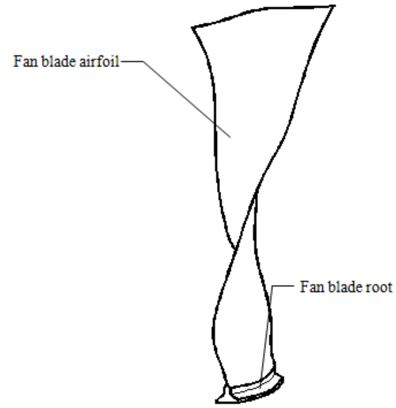


Fig. 1. Fan blade manufactured as a separate parts

These blades are subjected to very high stress caused by inertia forces generated by the blade's rotational motion and bending forces caused by the air pressure difference exerted on the pressure side and the suction side of the blade. In order to reduce these stress forces, engineers continuously made design changes in order to reduce the fan weight while maintaining the same strength of the component.

Manufacturing fan blades out of carbon fiber epoxy composites was an early target for the engineers. Carbon fiber fan blades have a long history behind them and how engineers managed to achieve this goal.

Fig.2. Fan *blisk* manufactured by COMOTI during SILENCE-R project

Rolls-Royce back in 1960 were the first aerospace company that has attempted to manufacture these fan blades. [2]

This revolutionary idea nearly broke the company. Rolls-Royce tried to make composite fan blades for the engine RB211 for powering of the Lockheed L-1011 TriStar aircraft. This attempt bankrupted the company which was saved at the last minute by the government through nationalization in 1971. The composite material called Hyfil which was developed by RAE Farnborough was not resilient enough. For this reason, the composite matrix failed during bird-strike tests (this test is done in order to check that the fan blades impact resistance with birds that are thrown intentionally in the engine fan does not affect the safety of entire aircraft). This failure convinced Rolls-Royce to abandon the idea of fan blade made of composite materials and to change their research to direction of hollow titanium alloy blades. This type of blade is manufactured through super-plastic forming and diffusion bonding (a sandwich made of three titanium sheets is firstly diffusion-bonded and then super-plastically formed into a complex 3D shape in a mould at high temperature). Finally a high pressure inert gas is used for separating of the two halves. Thus Rolls Royce created a technological reference for this type of engine blade.

Rolls-Royce's most important competitor, General Electric, in 1995, launched GE90 turbofan which had its fan made out of composite materials manufactured through a successful process, thus proving that the technology works and can be applied [3].

Near the root, the blades of GE90 turbofan are made of up to 1000 plies of uni-directional carbon prepreg tapes. Thickness of blade decreases progressively from 4 inches near the root to ¼ inches at the tip. The plies are cut using ultrasound in shapes designed in CATIA or AutoCAD. The preformed blade is placed in a mould and after that resin is injected. The curing process takes place in an autoclave, having a controlled temperature and pressure environment. The polymerising process is taking place in an autoclave in a high-precision press. In this state the blade must be still shaped through CNC milling to final dimensions. Finally, the composite blades are inspected through non-destructive technology. The leading edges, tips and trailing edges of blade are protected by thin fairings made of thin titanium sheet which have the role to reduce impact of bird strike on blade.

Meanwhile, for the CFM56 and LEAP engines, General Electric and its partner Safran (Snecma, France) have developed a 3D woven technology in collaboration with Albany Composites. GE and its partner Safran (Snecma) achieved a production of 14.000 fan blades per year [3].

This determined Rolls-Royce to re-launch research for manufacturing carbon fiber composite fans and casings for future aero-engines [2]. Rolls-Royce considers that developing fans and associated casings made out of carbon fiber composites are a key feature for manufacturing future advanced turbofans leading to reduction of weight of around 680 (kg) per aircraft. Rolls-Royce's technology is based on using carbon fiber/epoxy prepreg and automated carbon fiber placement technology. The blades are machined, coated and after that titanium leading, trailing and tip edges are bonded by the blade edges. Rolls-Royce evaluated that titanium attachments represent only 3% of the blade weight. At the end of the process the blades are inspected with ultrasounds and are subjected to mechanical tests. Finally the composite blades are coated with special coatings to protect it against normal environmental wear and tear.

Simultaneously, composite fan track liners and rear case liners began to be manufactured for Rolls-Royce Trent turbofan engines.

II. THE BIONIC MODELS OF NATURE

Although the results of General Electric and Rolls-Royce are remarkable, it seems that the standards given by Nature are far more advanced (Fig.3) [4]. The bird bone is called 'pneumatic bone' because it is hallow and the cavity is filled with air. The exterior of the bone is composed of a thin and dense layer which is reinforced by a multitude of internal struts. This is a natural principle because a similar structure is present in feathers. Both bird wing bones and feathers are subjected to bending and torsion. In both cases (bending and torsion) the maximum stress is achieved on the external structure being minimum in the center near the neutral axis. Inertia moment and Young's modulus, E, give the stiffness of a structure during bending. Because of this the most important are external structures. In the case of torsion the situation is the same, i.e. stiffness is given by the polar inertia moment and torsion modulus, G.

Bird's bone density is 2.15 (g/cm^3) while the total density of a flying mammal is 2 (g/cm^3) [4]. However due to the fact that internal cavity is empty except with the existence of the internal struts which are thin and light, the apparent density is about ρ=0.3 (g/cm^3) which is 5 times lower than the average density of carbon fiber epoxy composite which is ρ=1.5 (g/cm^3).

On the other hand, in both cases (bending and torsion) the existence of internal struts inside the bone is necessary for maintaining the stability of the external structure and to avoid overstress caused by buckling. This is achieved by a triangular disposition of struts as it is presented in Fig. 3 [4]. Inside a bird bone, thickness and disposition of the struts is not constant, this depends on local stress forces. The thickness and the number of struts is larger in proximity of the articulations where torque and bending are maximum and rare and thin at end of bone where torque and bending are minimum. This kind of structure was already copied in a specific way by the aircraft manufacturers. In Fig. 4 there is a aircraft wing section which has a structure resembling internal bird bone structure [4].

In the next chapter will present how this natural technology can be applied in a specific manner manufacturing aerospace components.

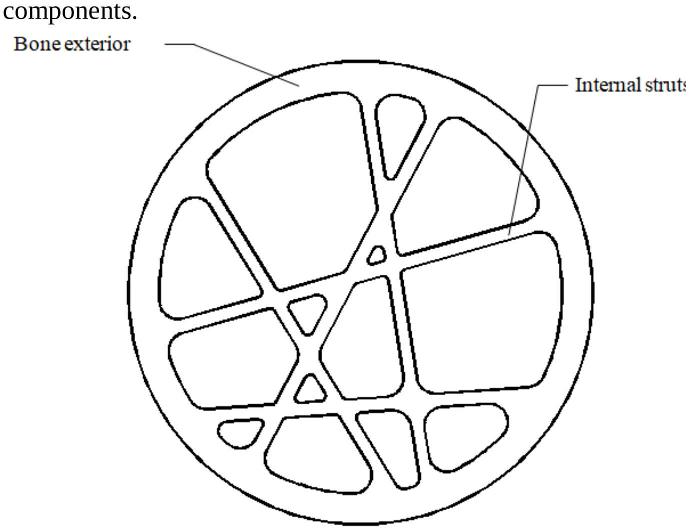


Fig. 3. Bird bone structure [4]

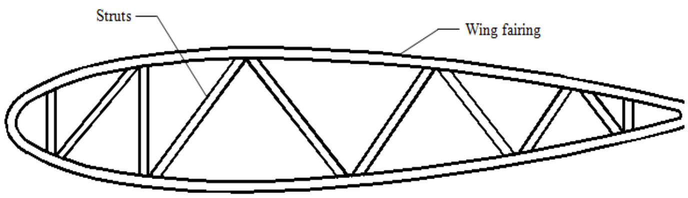
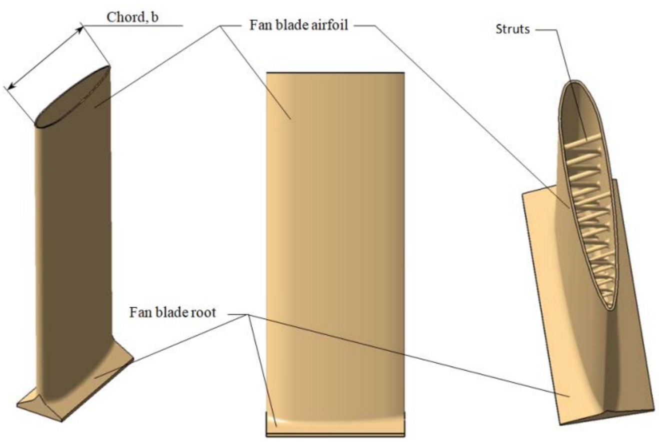


Fig. 4. Aircraft wing transverse structure

III. EXAMPLES OF BIONIC STRUCTURES USED IN AIRCRAFT COMPONENTS

Engine fan blades should have a structure similar to the one presented in chapter II, Fig. 3. In chapter III, Fig. 5 there is such a structure represented. The simplified design of the engine fan blade makes numerical and analytical calculations easier, thus making the phenomena easier to understood. In reality the configuration of a fan blade is as presented in Fig. 1. In Fig. 5a) CATIA image of a hollow fan blade is presented, in Fig. 5 b) image of a side of fan blade and in Fig. 5 c) image of a fan blade with multiple struts.



Fíg. 5. a) Hollow fan blade without struts (left)
b) Side view of a fan blade (center)
c) Hollow fan blade with struts (right)

Numerical and analytical calculations of these blades presented at points IV and V will show the advantages of bionic design in comparison with standard design.

IV. COMPARATIVE RESULTS OF STRUCTURAL ANALYSIS

Structural analysis has been done for the case a) Fan blade without internal struts and c) fan blade with internal struts, which are the simplified configurations for the fan blade.

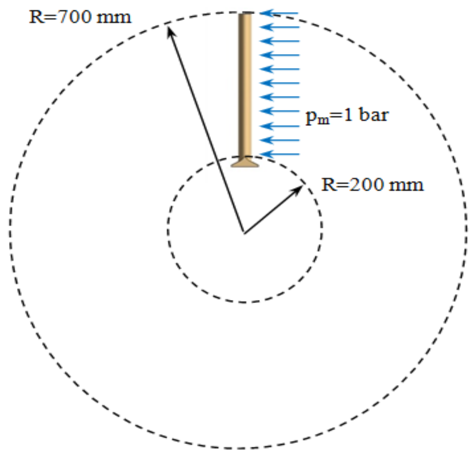


Fig. 6. Fan blade dimensions and blade loading

It was assumed that the fan blade (Fig.6) is rotating at a speed of 4500 (rpm) and its diameter is 1400 (mm) and an average pressure of p_m= 1 (bar) was applied on the pressure side of the fan blade. The composite material density is 1,472 (g/cm^3). In order to compare the two cases the criteria for stress and displacements were used and by introducing the Hashin-Fabric failure index the stress was evaluated and analyzed. The results or calculations - displacements of the leading and trailing edge and the distribution of the Hashin-Fabric index on OZ axis are presented in Fig. 7 a & c. It can be seen that the effect of the struts on reducing the displacements of the blade bending is significant. The rotation angle (twist angle) of the blade with struts is 10% smaller than in a classic blade.

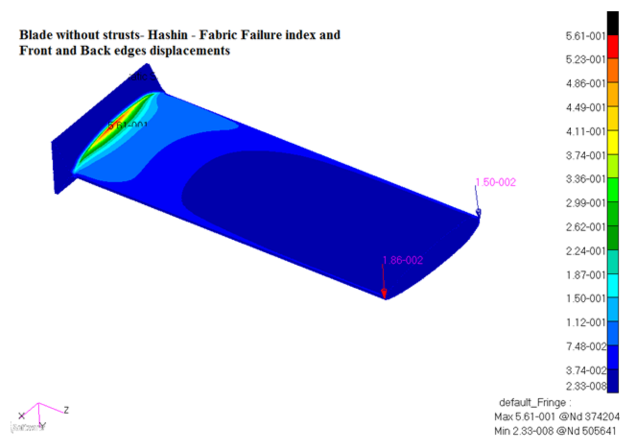


Fig. 7. a. Blade without struts – Hashin- Fabric failure index Fz and front and back edges displacements [m]

The leading edge displacement for the upper blade (see Fig.7.a) is the same 1.5 (cm) but the trailing edge displacement of the blade without struts is 1.86 (cm), while the blade with struts has a back edge displacement of the 1.64 (cm). The twist angle of the blade is defined by the relation:

$$\varphi = \frac{V_f - V_b}{a} \quad (1)$$

where, φ is the twist angle, V_f is the leading edge displacement, V_b is the trailing edge displacement and a is the chord length of fan blade. Thus the twist angle of the blade without struts is 2.57 times bigger (1.86-1.5=0.36; 1.64-1.5=0.14; 0.36/0.14=2.57). The maximum failure index Fz for the blade without struts is 0.561. In case of the blade with struts the maximum failure index is 0.713 but only at the joint between airfoil and struts near the blade root. This is because the strut should be fixed directly by the blade root in that area and secondly, the density of the struts, their diameter and the bending radius of the struts by adjacent surfaces should be larger. Future simulations will take into account these preliminary observations.

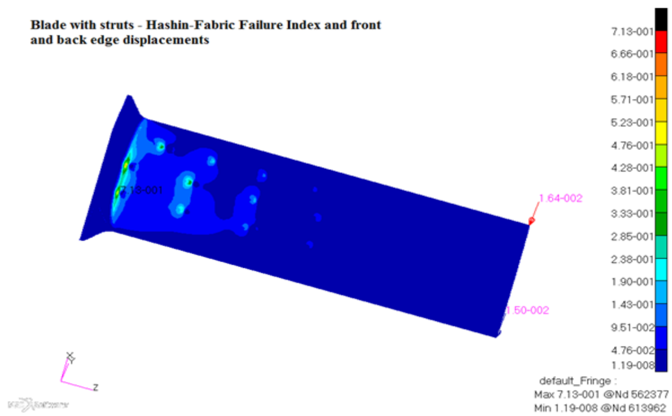


Fig. 7. c. Blade with struts – Hashin-Fabric failure index Fz and leading edge and trailing edge displacement [m]

V. A SIMPLE EXPLANATION FOR DECREASIG BENDING STRESS AND INCREASING RIGIDITY

If the analysis is done on a blade model which has a section composed of two rectangles which are not connected with struts then there is a decrease in the bending stress intensity (case I, Fig. 8). If it is connected with struts (case II, Fig. 9).

In the first case I, the approximation of the inertial moment can be done by assuming that two parts are bending independently. The inertia moment for each part is given by the following classic equations [5]:

$$I_{1z} = \iint_{D1} y^2 dx \cdot dy = \frac{a \cdot b^3}{12} \quad (2)$$

where, a - blade chord, b – thickness of the blade's airfoil. The bending resistance module is [5]:

$$W_{1z} = \frac{\frac{a \cdot b^3}{12}}{\frac{b}{2}} = \frac{a \cdot b^2}{6} \quad (3)$$

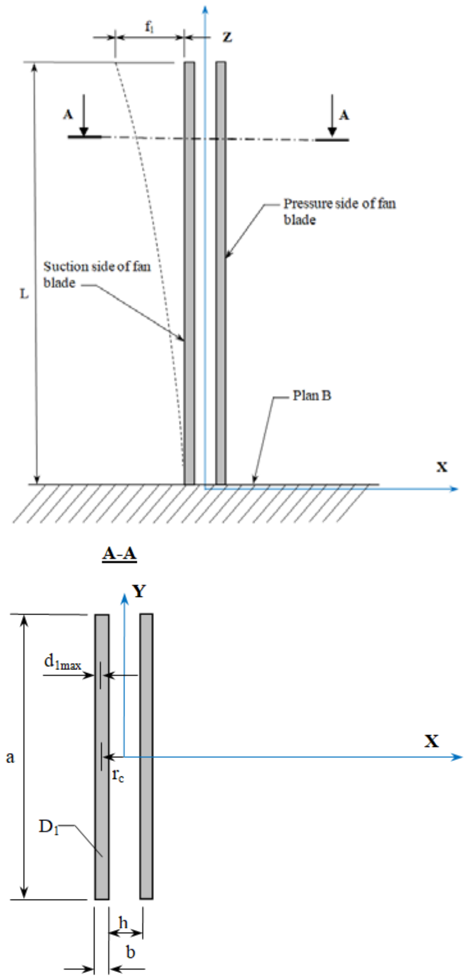
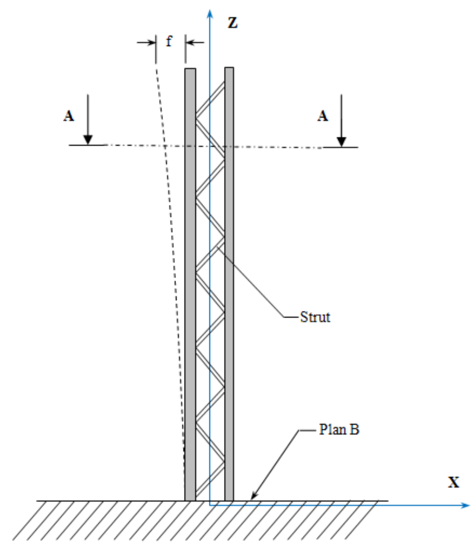


Fig. 8. Case I. Blade model composed of two rectangles without struts



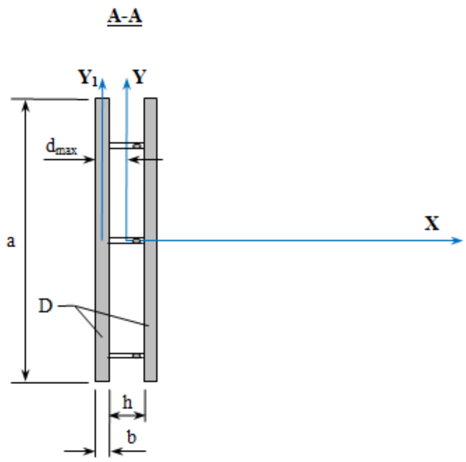


Fig. 9. Case II. Blade model composed of two rectangles with struts

The maximum bending moment reached in section B [5]:

$$M_z = \frac{L}{2} \cdot \iint_{D2} p \cdot dy \cdot dz = \frac{L}{2} \cdot p \cdot a \cdot L = \frac{p \cdot a \cdot L^2}{2} \tag{4}$$

where, *p* is the average air pressure difference on fan blade surface and *L* is the height of fan blade airfoil.

Assuming that each rectangle supports half the bending moment, the maximum bending moment stress is achieved in the plane B, at the root of the fan blade [5]:

$$\sigma_{1max} = \frac{\frac{M_z}{2}}{W_{1z}} = \frac{\frac{p \cdot a \cdot L^2}{4}}{\frac{a \cdot b^2}{6}} = \frac{3 \cdot p \cdot L^2}{2 \cdot b^2} \tag{5}$$

Because the chord *a* is much longer than the distance *h* and the thickness *b*, then the assumption that each part of the blade is bending independently can be made.

$$I_z = \iint_D y^2 dx \cdot dy = 2 \cdot a \cdot b \cdot y_c^2 = 2ab\left(\frac{h}{2} + \frac{b}{2}\right)^2 = 2ab\frac{(h+b)^2}{4} = \frac{ab\,(h+b)^2}{2} \tag{6}$$

where, y_c is the distance to the center of each rectangle.

The resistance module at bending is B [5]:

$$W_z = \frac{I_z}{d_{max}} = \frac{\frac{ab\,(h+b)^2}{2}}{\left(\frac{h}{2}+\frac{b}{2}\right)} = ab(h+b) \tag{7}$$

The maximum bending stress results from the following relation [5]:

$$\sigma_{max} = \frac{M_z}{W_z} = \frac{\frac{p \cdot a \cdot L^2}{2}}{a \cdot b(h+b)} = \frac{p \cdot L^2}{2 \cdot b(h+b)} \tag{8}$$

From (5) and (8) one can see that:

$$\frac{\sigma_{max}}{\sigma_{1max}} = \frac{\frac{p \cdot L^2}{2b(h+b)}}{\frac{3p \cdot L^2}{2 \cdot b^2}} = \frac{b}{3(h+b)} \tag{9}$$

Obviously, $\sigma_{max} \gg \sigma_{1max}$ for any existent values for *b* and *h*:

Doing simple calculations [5], one can find that the maximum displacement of fan blade, *f*, at tip is much smaller in case II that in the case I, i.e:

$$\frac{f_{max}}{f_{1max}} = \frac{I_z}{I_{1z}} = \frac{\frac{ab\,(h+b)^2}{2}}{2 \cdot \frac{ab^3}{12}} = \frac{3(h+b)^2}{b^2} \tag{10}$$

Equation 10, shows that the fan blade with struts has a smaller flexibility than the fan blade without struts. This is considered an advantage.

VI. THE PROPOSED TECHNOLOGY

The originality of the proposed technology consists in using a complex casting made out of low melting alloy model for forming the complex shape carbon fiber epoxy composite part. The part is made out of carbon fiber struts (for example Torayca T300 3K[6]) impregnated with a high temperature epoxy resin (Resoltech HTG 240 and hardener HTG 245 [7], [8]), covered with carbon fiber fabric layers and cured in a steel mold in an controlled autoclave where pressure and temperature can be set. Low melting alloys have a melting temperature of under 300 °C. Low melting alloys can contain the following elements: zinc, tin, tellurium, gallium, bismuth, indium, cadmium, antimony, thallium, mercury and lead. Commonly used alloys have a melting temperature of under 150 °C. Such alloys contain: bismuth, tin, lead, cadmium and indium. A special category is reserved for alloys that melt in hot water (100 °C). Composition of some common used low melting alloys is given in Table 1 [9].

Table 1. Examples of low melting point alloys [9]

Inventor's name	**PN-91 Standard**	**ASTM B774-400 standard**	**Chemical Composition**	**Melting point**
Field's alloy	-	-	$Bi_{32.5}In_{51}Sn_{16.5}$	47 °C
Wood's alloy	TBC12	158	$Bi_{50}Pb_{25}Sn_{12.5}Cd_{12.5}$	70 °C
Lipowitz's alloy	TBC13	-	$Bi_{50}Pb_{27}Sn_{13}Cd_{10}$	80 °C
Matrix's alloy	TBC14	-	$Bi_{53}Pb_{28.5}Sn_{14.5}$	108 °C
Newton's alloy	TBC19	203	$Bi_{50}Pb_{31.2}Sn_{18.8}$	96 °C
Lichtenberg's alloy	TBC20	-	$Bi_{50}Pb_{30}Sn_{20}$	92 °C
Erman's alloy	-	-	$Bi_{50}Pb_{25}Sn_{25}$	93 °C
Roses alloy	-	-	$Bi_{50}Pb_{28}Sn_{22}$	109 °C

The model is obtained through permanent mold casting of low melting alloy (gravity die-casting), see Fig. 10.

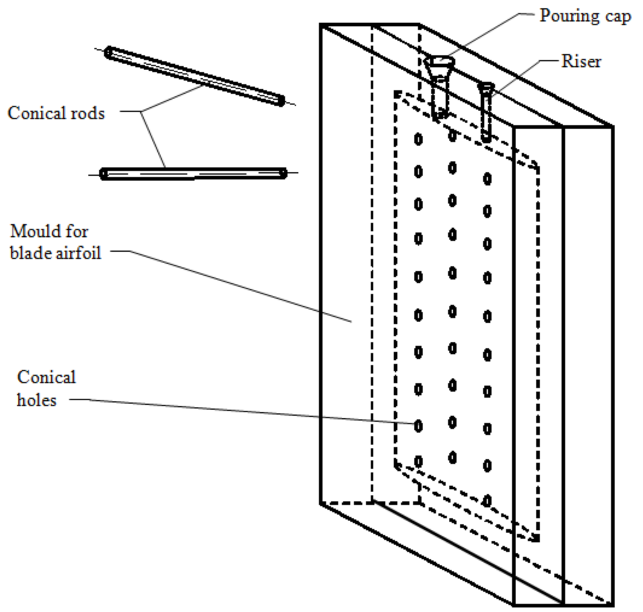


Fig. 10. Pouring mould for low melting alloys

The mould is composed of two halves made from cast grey iron or steel and it is reusable. A good material for manufacturing a mould is grey iron having composition C≈3.2%, Si≈1,9%, Mn≈0,7%, P-max 0.25%, S-max 0.12% having tensile strength σ≈ 250 (N/mm^2).

The mould in Fig. 10 is composed out of two halves made out of grey cast iron or steel and it is reusable. A good material for mould manufacturing is grey iron with the following composition: C≈3.2%, Si≈1,9%, Mn≈0,7%, P - max 0.25%, S-max 0.12% having tensile strength σ≈ 250 (N/mm^2). 5D machine milling is used to manufacture and give shape to the two halves of the mould with a final roughness of about 0.4-0.6 (Fig. 10). In both halves of the mould, precise conical holes are drilled. These holes allow for the conical rods to be mounted which create space for the future carbon fiber epoxy struts. The mounting clearance between rods and mould halves is small of about 0.02-0.04 (mm) in order to avoid material loss during pouring the melted alloy. The tip angle of conical rods is ~2°.

After pouring and cooling, the conical rods and the two halves of the mould are removed. Using a tool presented in (Fig. 11), a carbon fiber bunch impregnated with HTG 240 epoxy resin is introduced in holes created by conic rods in the cast low melting alloy. Fixing of bunch by sewing tool is done by a coiled wire. The process is similar to sewing. A technological possibility is as the carbon fibers bunch to be pre-introduced in carbon fiber sleeves (Fig. 11). This will confer to the struts additional strength.

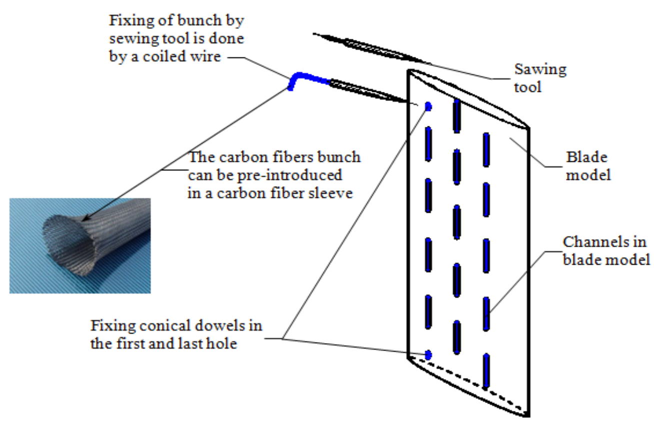


Fig. 11. *Sewing* the fan blade casting

At the beginning and at the end of the *sewing* process, the bunch of fibers are fixed with conical dowels made out of composite material pressed flush inside the holes. At the surface of the casting mould the bunch of fibers enter the existing channel created during pouring of low melting alloy.

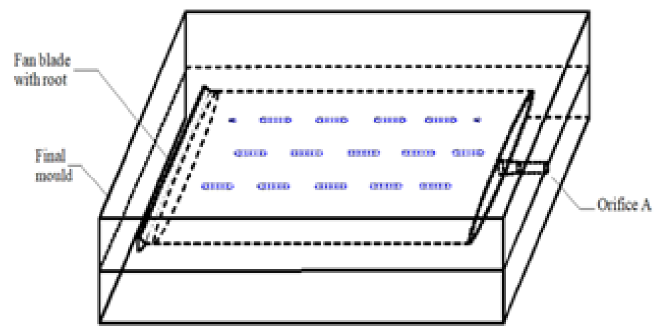


Fig. 12. Polymerizing fan blade in final form

Afterwards, carbon fiber fabric layers are applied with epoxy resin on the external surfaces of the cast model of the fan blade and in the space which form the blade root of the final blade mould (Fig. 12) and it is then cured under low pressure 1-2 (bars) in the oven. The needed curing temperature is 30-40 °C under the melting point of the alloy used. The mould is then turned vertically with the orifice A facing downwards and the whole mould is heated to 20-30 °C over the melting point of the low melting alloy. With the orifice A facing downwards this allows the melted alloy to flow in a collecting vessel.

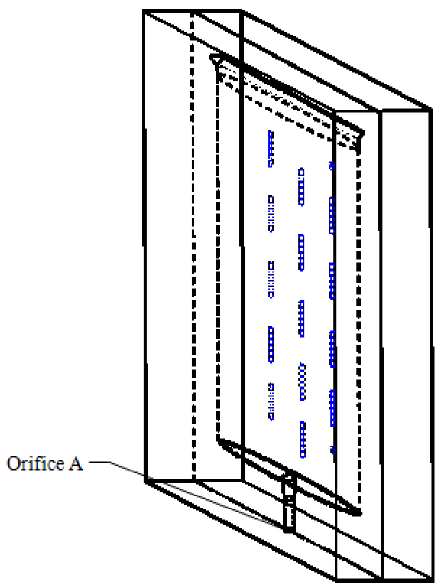


Fig. 13. Evacuation of low melting alloy

Finally, the polymerized blade takes the final dimensions after 5D machine milling, polished and painted. A thin titanium V piece is applied with adhesive on the fan blade leading edge in order to increase the strength of the blade at impact with birds (application of these titanium pieces is currently applied on currently manufactured carbon fiber blades [10].

VII. OTHER AEROSPACE COMPONENTS WHICH CAN BE MANUFACTURED USING THIS TECHNOLOGY

This technology can be applied in manufacturing other engine components like: fan vanes, fan housings, compressor housings with important weight savings.

Due to the same reasons the technology can be applied on rocket components which are working at low temperatures.

In Fig. 14 there are presented compressor components of a turbofan housing which could be manufactured using this bionic technology.

The new technology can be used to manufacture fan housings, fan vanes this contributing to an increase in engine strength and rigidity while decreasing weight of other components and engine overall weight.

Other applications for this new technology could be in small aircrafts, for example in USA there is a desire to develop a small passenger aircraft (6 passengers). This type of transportation system should use small aircraft which incorporates new technologies developed by NASA and FAA (Fig.15) [11]. In this case, the bionic technology (Fig. 5.c) is more obviously preferable for wing, horizontal and vertical stabilizer manufacturing instead of the classic which uses spars and ribs. Using this new technology is correlated with development of new propulsion systems (jet fuel diesel engines) allowing for better control of resonance frequencies for not coinciding with working frequencies of diesel engine rotors.

This new technology proposed in this paper can be applied in non-aerospace components but costs could be prohibitive.

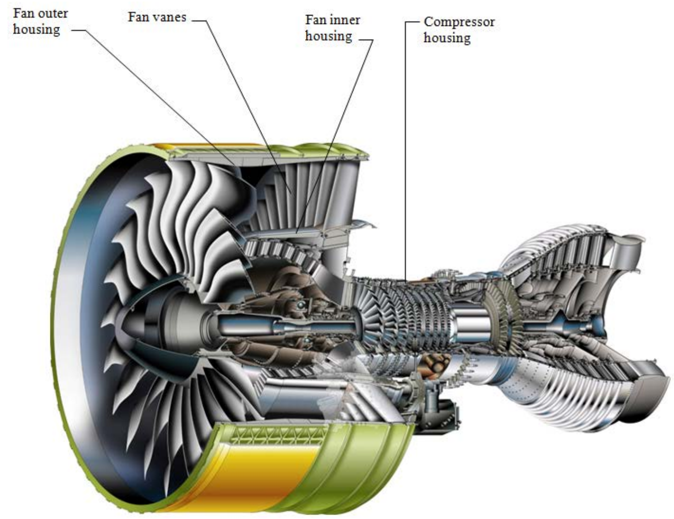


Fig. 14. Turbofan engine components that can be manufactured with the bionic technology

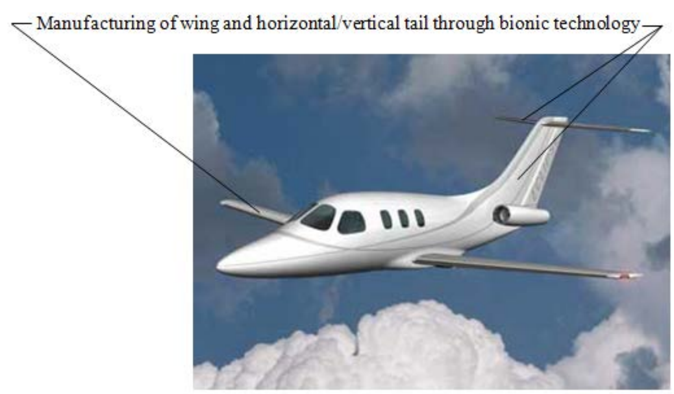


Fig. 15. Incorporating new technologies developed by NASA and FAA used in small passenger aircraft

VIII. CONCLUSIONS

The present paper proposes a bionic technology for aersospace components.

This technology has been inspired by the structure of bird bones which have internal struts leading to a very high strength for a minimum weight.

For this reason the technology can be applied for manufacturing of aerospace components which must be very light and simultaneously present good strength properties. Such components are fan blades for ultrahigh bypass ratio engines (UHBP), propellers and counter-rotating propellers, fan vanes, fan housings, compressor housings, rocket components etc.

Simple calculations show that when this technology is applied minimum average densities are achieved for aerospace components.

The technology is simple and can be applied with existing equipment and materials:

- Producing models made out of low melting alloys poured in moulds of grey iron or steel;
- Low diameter holes are drilled the in model by means of conical rods during melting process. A sewing process is used then for creating of a net of oriented struts made of carbon fiber in the model;
- Finally, the model is wrapped in carbon fiber fabric impregnated with epoxy resin, pressed in final mould and cured in autoclave;
- The final step of the manufacturing consists of heating the alloy to a temperature of 20 – 30 °C over the melting point melting it and flowing into a collecting vessel.

There is room for improvement for the presented technology. One improvement can be made by using graphene or very long carbon whiskers when such long mono-crystal carbon fibers will be produces.

ACKNOWLEDGEMENT

The present technology is the result of original research.

IX. REFERENCES

[1] SILENCE-R, Project ID: G4RD-CT-2001-00500, Funded under FP5-GROWTH, 01.04.2001-31.07.2007 - Fan blisk manufactured by COMOTI

[2] Mash, G., Composites Get in Deep with New-Generation Engine, 22 December 2006

[3] Upadhyay, R. & Sinha, S., GE-90 and Derivative Fan Blade Manufacturing Design, 2017

[4] Sullivan, T. N., Wang, B., Espinosa, H.D., Meyers, M.A., Extreme Lightweight Structures: Avian Feathers and Bones, Elsevier, Materials Today, Volume 20, Number 7, September 2017

[5] Buzdugan, G., Rezistenta Materialelor, Ed.X revizuita, Editura Tehnica, Bucuresti, 1974

[6] High performance carbon fiber Torayca – “Toray” Innovation by Chemistry

[7] High TG Structural Infusion Epoxy Systems – Resoltech HTG 240, Hardener HTG 245, Technical Data Sheet – 14/03/2018

[8] Resoltech Advanced Technology Resins – Resoltech Composite Tooling Range

[9] Stabik, J., Wierzbick, L., Influence of Low Melting Point Alloy on Strength Properties of Epoxy Resin, Institute of Engineering Materials and Biometals, Silesian University of Technology

[10] Kellner, T., The Art of Engineering: The World’s Larget Jet Engine Shows Off Composite Curves – General Electric Reports, 28/04/2016

[11] NASA Facts, Small Aircraft Propulsion: The Future is Here, Glenn Propulsion Program Opens the Door to a New Era in General Aviation, Glenn Research Center