

A Study of the Thermo-Mechanical Behavior of a Gas Turbine Blade in Composite Materials Reinforced with Mast



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ABSTRACT

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The turbine blades are subjected to high operating temperatures and high centrifugal tensile stress due to rotational speeds. The maximum temperature at the inlet of the turbine is currently limited by the resistance of the materials used for the blades. The present paper is focused on the thermo-mechanical behavior of the blade in composite materials with reinforced mast under two different types of loading. The material studied in this work is a composite material, the selected matrix is a technical ceramic which is alumina (aluminum oxide Al_2O_3) and the reinforcement is carried out by short fibers of high modulus carbon to optimize a percentage of 40% carbon and 60% of ceramics. The simulation was performed numerically by Ansys (Workbench 16.0) software. The comparative analysis was conducted to determine displacements, strains and Von Mises stress of composite material and then compared to other materials such as Titanium Alloy, Stainless Steel Alloy, and Aluminum 2024 Alloy. The results were compared in order to select the material with the best performance in terms of rigidity under thermo-mechanical stresses. While comparing these materials, it is found that composite material is better suited for high temperature applications. On evaluating the graphs drawn for, strains and displacements, the blade in composite materials reinforced with mast is considered as optimum.

1. INTRODUCTION

Nowadays, the improvement of modern turbo machines efficiency, especially gas turbines, is achieved mainly by increasing their temperature level in the combustion chamber. The maximum temperature at the inlet of the turbine is currently limited by the resistance of the materials used for the impeller blades. The deterioration of the thermal barrier systems occurs by peeling the ceramic layer. The bared metal is then exposed to dangerously hot gases from the combustion chamber. So far, numerous studies have been conducted on the materials of gas turbine blades [1]. Uses ANSYS 16 for static, thermal and modal analysis of the distribution of thermal stress and temperature in the gas turbine blade of different titanium alloy, stainless steel and aluminum 2024 materials [2]. A study was carried out by other authors [3] on thermo-mechanical fatigue behavior for material Inconel 738. The work is mainly focused on the resistance of solid turbine blades to investigate the balanced thermal and structural performance of the blade for Inconel 738 materials and Inconel U500. A coupled thermo-mechanical simulation of a coated vane is used to model the flaking of the thermal barrier that occurs under the service conditions of the blade [4]. Another work [5] An attempt to analyze the gas turbine blade by comparing the

Hastelloy X material to Nimonic alloy 80A and Inconel 625. Alain KÖSTER [6] has carried out a work on Modeling of Super alloy damage in thermal fatigue. Whereas M. Pierre-Yvan THERY [7] has conducted a work on the experimental and modeling scaling realized on two particular thermal barrier systems and a comparison was proposed. Then Antoine MILLECAMP [8] has carried out numerical simulations for the study of blades dynamics and the influence of the contact, the wear and the thermo-mechanical forces on the vibratory behavior [9]. A study was carried out by other authors [10] on thermo-mechanical fatigue behavior for two different materials (Inconel 718 and titanium T6). The work is mainly focused on the resistance of solid turbine blades to investigate the balanced thermal and structural performance of the blade for N 155 materials, X nickel base super alloy and Inconel 625. Finally [11] has studied a new thermal insulation ceramic that can operate at higher temperatures and based on partially stabilized zirconia with uterus. This is a logical continuation of the work conducted for several years at ONERA on the search for new ceramic compositions. It is from these considerations that the study of thermo-mechanical behavior on a composite material is initiated. The objective of optimizing such a composite material is to design a fin which supports the bulk of the thermo-mechanical loading. The

objective of this work is to evaluate the thermo-mechanical behavior of fins in composite materials with reinforcement in short fiber (mast) high modulus carbon.

2. MATERIALS AND METHODS

To observe the thermo-mechanical behavior of blade in composite material, in this study, we will calculate the displacements and the deformations of the blade in composite material with random orientation and super-alloy. The characteristics of the gas turbine blade manufacturing materials are listed in Table 1 and 2.

Table 1. Mechanical and thermal characteristics of super alloys [1]

Materials	Titanium Alloy	Stainless Steel Alloy	Aluminum 2024 Alloy
Density [Kg/m ³]	4700	8025	2750
Young's modulus [GPa]	205	200	73
Poisson's ratio	0.33	0.30	0.33
Yield strength [MPa]	1000	1050	470
Coefficient of thermal expansion 10 ⁻⁶ °C	8.8	14.5	23.3

Table 2. Mechanical and thermal characteristics of high modulus carbon (HM) and alumina [12]

Materials	Carbon (HM)	Alumina (Al ₂ O ₃)
Density [Kg/m ³]	1800	3700
Young's modulus [GPa]	390	380
Poisson's ratio	0.35	0.25
Yield strength [MPa]	2500	1400
Coefficient of thermal expansion [10 ⁻⁶ (°C ⁻¹)]	0.8	8

3. DETERMINATION OF COMPOSITE MECHANICAL AND THERMAL CHARACTERISTICS

3.1 Mechanical characteristics

All equations of mechanical characteristics are given by Gay [12] and are recalled here for more clearness.

Longitudinal modulus of elasticity E_L is given by the following equation:

$$E_L = E_f V_f + E_m (1 - V_f) \quad (1)$$

Transverse modulus of elasticity E_T is expressed as follows:

$$E_T = \frac{E_m E_f}{E_f V_m + E_m V_f} \quad (2)$$

Then Poisson's ratio ν_L and ν_T is written as:

$$\mu_L = \nu_f V_m + \nu_m (1 - V_f) \quad (3)$$

$$\mu_T = \mu_L \frac{E_T}{E_L} \quad (4)$$

Finally the Longitudinal shear modulus G_L and Transverse shear modulus G_T expressed as follows:

$$G_L = \frac{G_m G_f}{G_f V_m + G_m V_f} \quad (5)$$

$$G_T = \frac{E_T}{2(1 + \nu_T)} \quad (6)$$

3.2 Thermal characteristics

Thermal characteristics are explained and resumed by Mallick [13].

The longitudinal thermal expansion α_L and Transverse thermal expansion are written as:

$$\alpha_L = \frac{(1 - V_f) \alpha_m E_m + V_f \alpha_f E_f}{(1 - V_f) E_m + V_f E_f} \quad (7)$$

$$\alpha_T = (1 - V_f) \alpha_m + V_f \alpha_f + (\alpha_f - \alpha_m) \frac{\nu_f E_m - \nu_m E_f}{\frac{E_m}{V_f} + \frac{E_f}{1 - V_f}} \quad (8)$$

3.3 Mechanical properties of the composite with mast reinforcement [14]

In this case the corresponding transformed reduced rigidity will be examined by:

$$\tilde{Q}_{ij} = \frac{\int_0^{2\pi} (\tilde{Q}_{ij}) \partial \theta}{\int_0^{2\pi} \partial \theta} \quad (9)$$

And the elastic modules of the mast layer are:

$$E_{m\hat{a}t} = \frac{(V_1 - V_4)(V_1 + V_4)}{V_1} \quad (10)$$

$$\nu_{m\hat{a}t} = \frac{V_4}{V_1}$$

$$G_{m\hat{a}t} = \frac{V_1 - V_4}{2}$$

With the expressions of V_i are:

$$V_1 = \frac{1}{8}(3Q_{11} + 3Q_{22} + 3Q_{12} + 4Q_{66});$$

$$V_2 = \frac{1}{2}(Q_{11} - Q_{22}); \quad (11)$$

$$V_3 = \frac{1}{8}(Q_{11} + Q_{22} - 2Q_{12});$$

$$V_4 = \frac{1}{8}(Q_{11} + Q_{22} + 6Q_{12} - 4Q_{66})$$

4. CHOICE OF COMPOSITE MATERIALS FOR THE REALIZATION OF THE BLADE

In our study we propose to realize a gas turbine blade in composite materials with reinforced mast. The material studied is a composite material, the selected matrix is a technical ceramic which is an alumina (aluminum oxide Al₂O₃) and the reinforcement is carried out by short fibers of carbon HM to optimize a percentage of 40% carbon and 60% of ceramics.

5. CHARACTERISTICS OF THE COMPOSITE MATERIAL

5.1 By the law of mixtures

The characteristics of composite material studied are presented below in Tables 3 and 4, respectively.

Table 3. Mechanical and thermal characteristics of the material studied

Young's Modulus [GPa]	E_L	384
	E_T	383.94
Poisson's ratio	ν_L	0.29
	ν_T	0.29
Shear modulus [GPa]	G_L	148.88
	G_T	148.82
thermal expansion [$10^{-6}(\text{°C}^{-1})$]	α_L	5.075
	α_T	4.96

5.2 By the law of the behavior of the composite with reinforcement mast

Table 4. Mechanical properties of the mast reinforced composite

Young's Modulus	Poisson's ratio	Shear modulus
$E_{\text{mât}}$ [GPa]	$\nu_{\text{mât}}$	$G_{\text{mât}}$ [GPa]
400.44	0.2797	156.45

6. NUMERICAL ANALYSIS

6.1 Gas turbine blade modeling

Three-dimensional model of the gas turbine blade is first modeled using the solid works software as described [1]. The meshing and analysis is done using ANSYS software by converting the design in IGS software and imported to Ansys for finding the stresses in the blade shown in Figure 1.

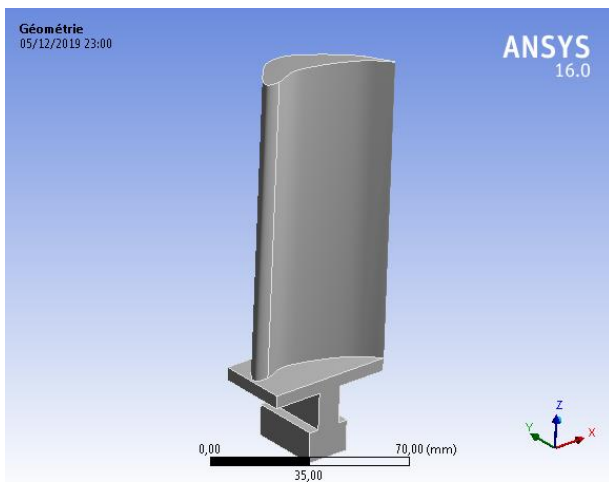


Figure 1. Gas turbine blade model

6.2 Model analysis of a gas turbine blade

It is proposed to study the mechanical behavior of a blade in composite material; thus, the analysis is carried out to determine the displacements and strains of the blade.

Boundary conditions are applied to the blade root, as applied by [1]. Three different types of loading were applied to the model. $F_a=3.82$ N, $F_t=248.199$ N, $F_c=38038.73$ N. In the solution part of the ANSYS, the blade forces are applied on the node located at the centroid of the blade. The blade is meshed with tetrahedron elements. The tetrahedral element is the simplest tessellated shape and is able to model arbitrary 3-D geometric structures. It is also well suited for automatic mesh generation. The mesh composed of 10987 elements and 20950 nodes. as shown in Figure 2.

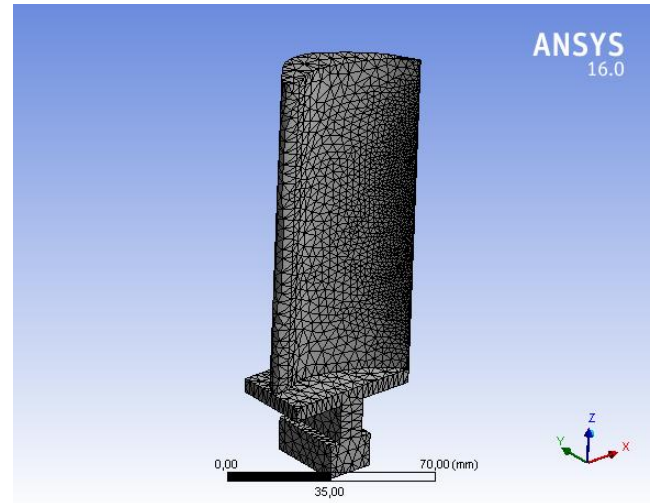


Figure 2. Finite element model of turbine blade

7. VALIDATIONS WITH LITERATURE

Due to the absence of the experimental study for that is why we compared the results obtained with the results obtained by Ahmed [1]. Structural analysis was carried out by applying the same limit conditions and mechanical forces selected materials for blade for validation. The desired comparison was made on the materials such as Aluminum 2024 Alloy, Stainless Steel Alloy and Titanium Alloy.

Figure 3 Show the displacement of the blade in the Titanium Alloy. the maximum displacement with a magnitude of 0.3915 mm.

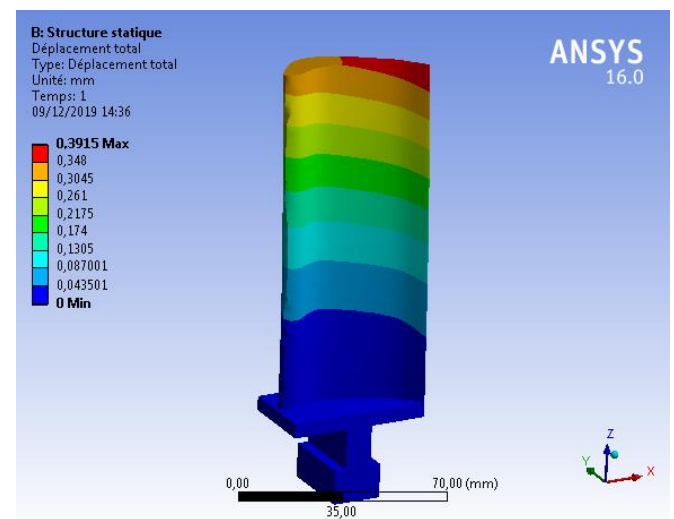


Figure 3. Resultant displacements of titanium alloy

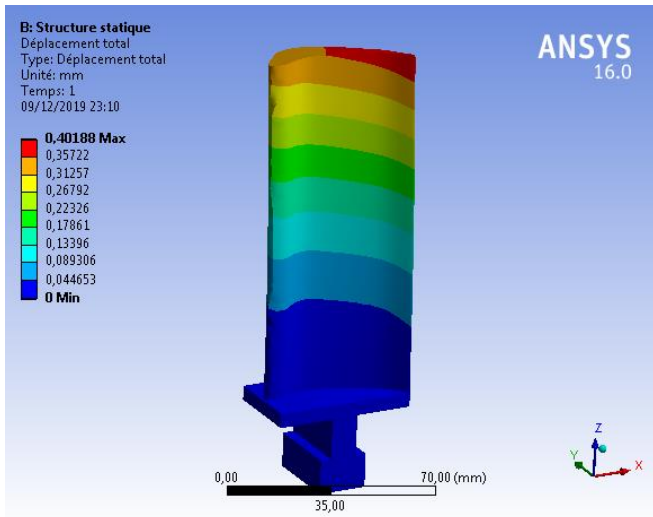


Figure 4. Resultant displacements of stainless steel alloy

Figure 4 shows the displacement of the blade in the Stainless-Steel Alloy. The maximum displacement with a magnitude of 0.40188 mm.

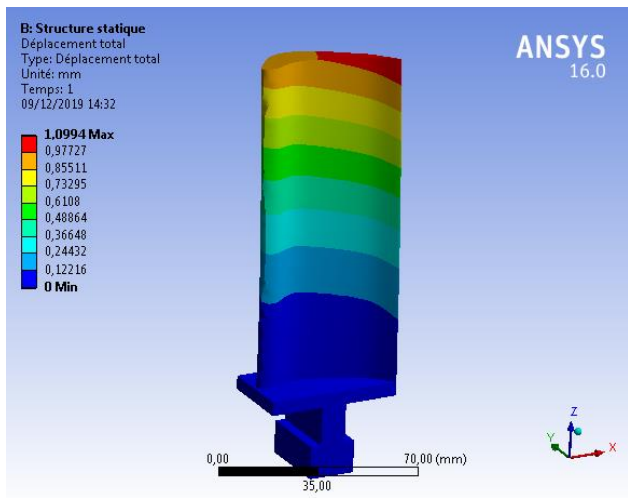


Figure 5. Resultant displacements of aluminum 2024 alloy

Figure 5 Show the displacement of the blade in the Aluminum 2024 Alloy. the maximum displacement with a magnitude of 1.0994 mm.

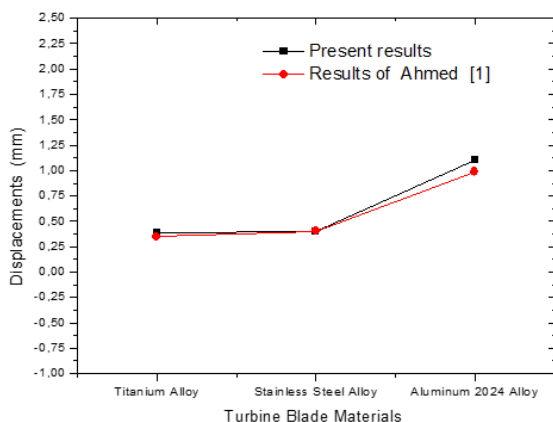


Figure 6. Turbine blade materials as a function of displacements

To confirm the reliability of our numerical study, we compared the results of our attempt with the previous results.

The results obtained and published by Ahmed [1] are used to illustrate the validity of the attempt. Figure 6 Show the comparison between the displacements results for the (present numerical study and numerical studied by Ahmed [1]). The results of displacement allowed us to note the conformity of the results given by the present numerical study and those obtained by Ahmed [1]. It should be noted that the precision of the numerical study gives very acceptable results.

8. RESULTS AND DISCUSSION

This work deals with modeling and analysis of the gas turbine blade were analyzed in ANSYS (Workbench 16.0) software. Different materials such as, Titanium Alloy, Stainless Steel Alloy, and Aluminum 2024 Alloy were compared to composite material.

8.1 Static analysis of blade

In this case, we will study the static analysis of the blade in the composite material under the given mechanical loading and boundary conditions. The results of the analysis are discussed below.

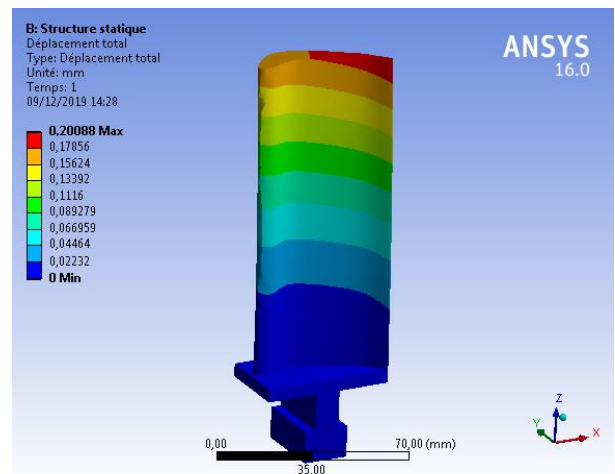


Figure 7. Distribution of the displacements of a blade in composite material

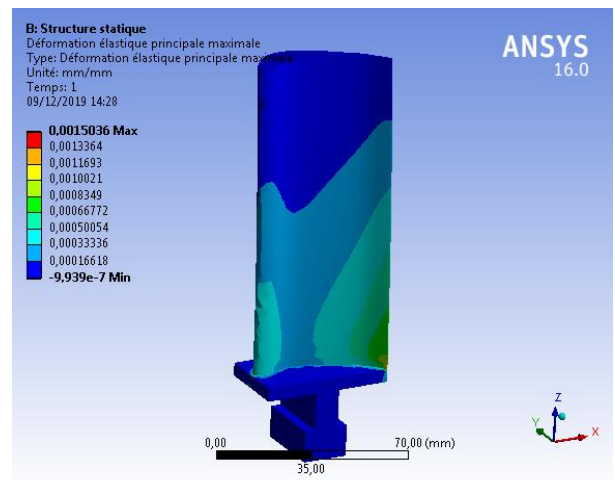


Figure 8. Distribution of the principal elastic strains of a blade in composite material

Figure 7 Show the displacement of the blade in the composite material. the maximum displacement with a magnitude of 0.20088 mm at the ends of the blade and the minimum displacement at the foot of the blade.

Figure 8 shows the maximum principal strains of 0.0015036 occur at the root section and on the pressure side of the gas turbine blade.

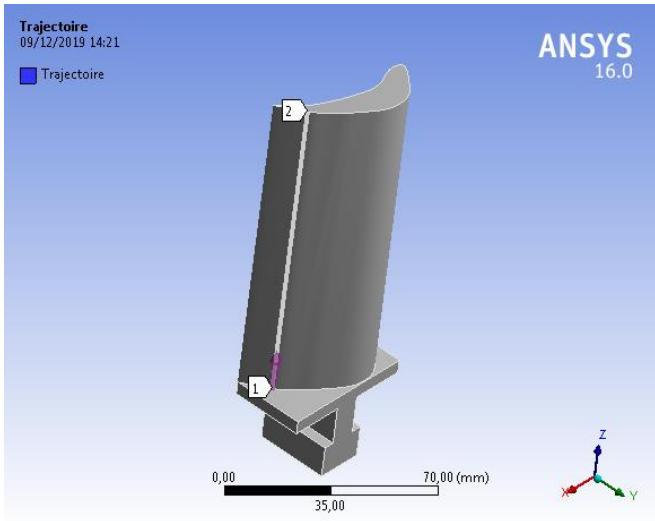


Figure 9. Direction of path

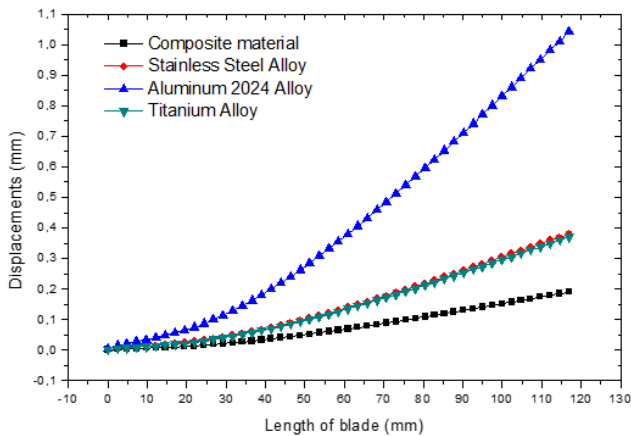


Figure 10. Comparing the displacements (for 4 materials) according to the length of the blade

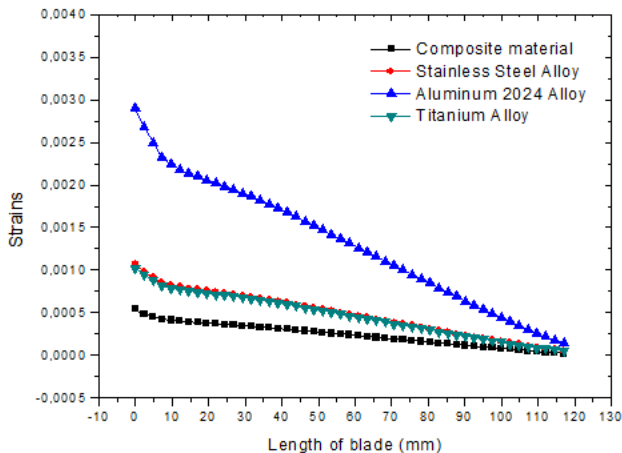


Figure 11. Comparing the strains (for 4 materials) according to the length of the blade

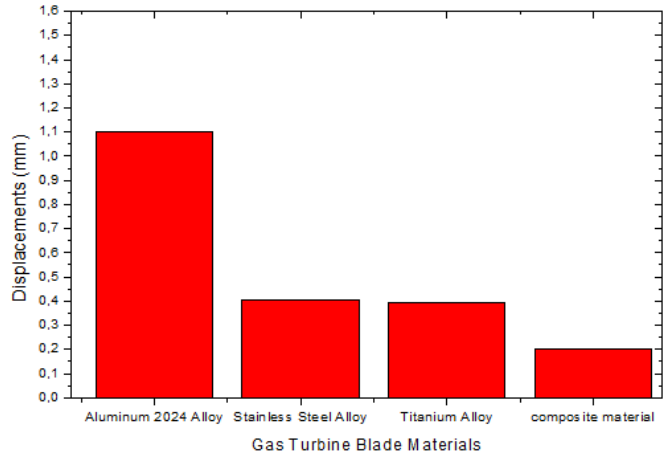


Figure 12. Turbine blade materials according to displacements

The results giving displacements and strains of blade in different materials we will plot according to the continuous path between point 1 and point 2 shown on the Figure 9.

Figure 10 shows the evolution of the displacements as a function of the blade length. It can be noted that the displacement of the composite blade gives better results in comparison with other materials. It is also observed that the maximum value of the displacement is localized in the blade of Aluminum 2024 Alloy material at 1.0416 mm, while the minimum value is found in the composite blade which at 0.19042 mm.

Figure 11 shows the evolution of the strains as a function of the blade length. It can be noted that the strains of the composite blade give better results in comparison with other materials. It is also observed that the maximum value of the strain is localized in the blade of Aluminum 2024 Alloy material at 0.0028978 while the minimum value is found in the composite blade which at 0.0004139.

Figure 12 shows the variation of displacements distribution for different materials of turbine blade. It is noted that the displacements are varying as the radial distance increases, the maximum value for Aluminum 2024 Alloy and the minimum value for composite.

8.2 Thermomechanical analysis of turbine blade

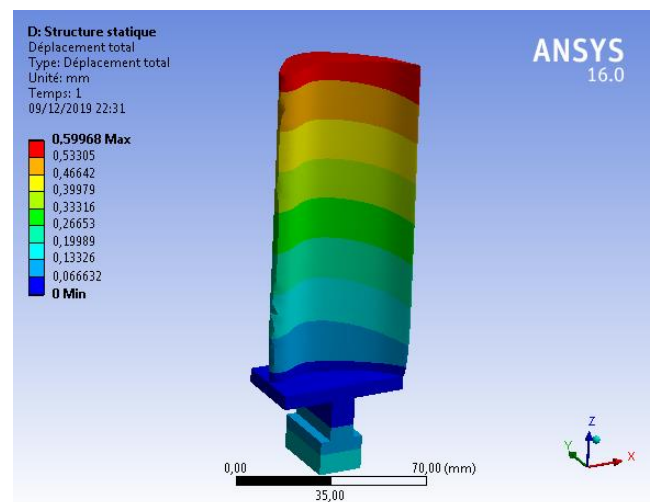


Figure 13. Distribution of the displacements of a blade in composite material

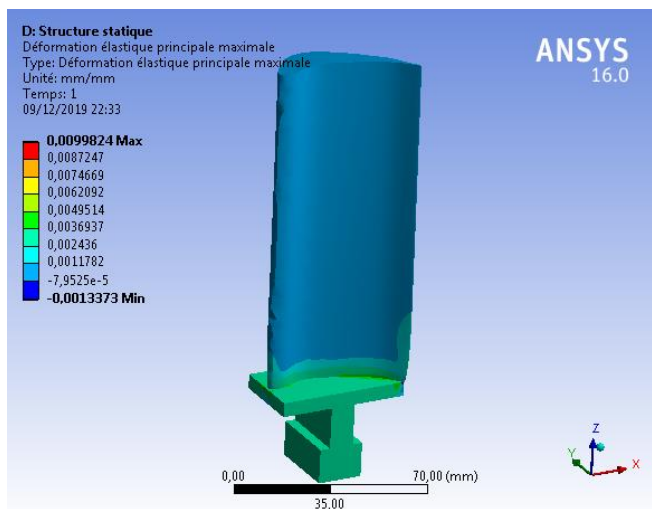


Figure 14. Distribution of the principal elastic strains of a blade in composite material

In this case, we will study the thermomechanical behavior of the blade under the same loading conditions and boundaries previously defined. under the influence of temperature $T=800^{\circ}\text{C}$.

A summary of the results obtained from the thermal analysis of the same previous materials.

Figure 13 shows displacements produced in the turbine blade due to action of centrifugal forces and temperature. It is observed that the maximum deformation of 0.59968 mm occurs at the tip section of turbine blade material and the minimum occurs at the root section. There was no evidence of rubbing between tip of the turbine blade and casing indicating elongation is within the limit.

Figure 14 shows the Strain distribution in the turbine blade due to action of centrifugal forces and temperature. It is observed that the maximum strain of 0.0099824 occurs at the root section and on the pressure side of gas turbine blade. Minimum stress occurs at the tip section pressure side of gas turbine blade.

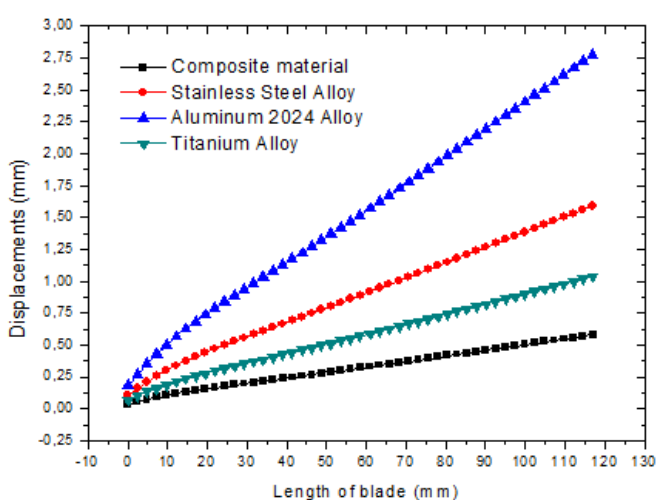


Figure 15. Comparing the displacements (for 4 materials) according to the length of the blade

Figure 15 shows the evolution of the displacements as a function of the blade length. It can be noted that the displacement of the composite blade gives better results in

comparison with other materials. It is also observed that the maximum value of the displacement is localized in the blade of Aluminum 2024 Alloy material at 2,7773 mm, while the minimum value is found in the composite blade which at 0,58044 mm.

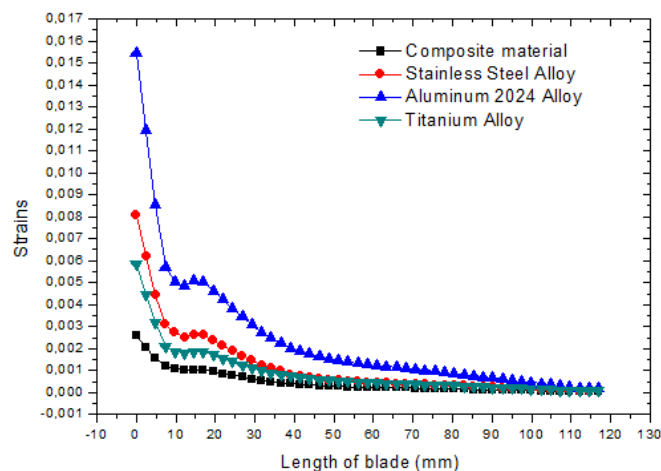


Figure 16. Comparing the principal elastic strains (for 4 materials) according to the length of the blade

Figure 16 shows the evolution of the strains as a function of the blade length. It can be noted that the strains of the composite blade give better results in comparison with other materials. It is also observed that the maximum value of the strain is localized in the blade of Aluminum 2024 Alloy material at 0.015668, while the minimum value is found in the composite blade which at 0.0025769.

8.3 Analysis of turbine blade at various speeds

In this case, we will compare the same materials under temperature ($T=800^{\circ}\text{C}$) with the change in the rotational speed value with three values: 4000 rpm, 6000 rpm, and 9000 rpm. Results on displacement and strain are shown in Tables 5, 6 respectively.

Table 5. Displacements of turbine blades made of different materials at various speeds

Materials	Displacements (mm)		
	4000(RPM)	6000(RPM)	9000(RPM)
Composite material	0.52029	0.52041	0.52071
Titanium Alloy	0.91156	0.91195	0.91291
Stainless Steel Alloy	0.4927	1.4934	1.4951
Aluminum 2024 Alloy	2.4133	2.4139	2.4153

Table 6. Strains of turbine blades made of different materials at various speeds

Materials	Strains (mm)		
	4000(RPM)	6000(RPM)	9000(RPM)
Composite material	0.01069	0.010684	0.01067
Titanium Alloy	0.020138	0.020115	0.020062
Stainless Steel Alloy	0.031627	0.03159	0.031508
Aluminum 2024 Alloy	0.053339	0.053301	0.053215

The results giving displacements and strains of blade in different materials shown in the Figures 17, 18.

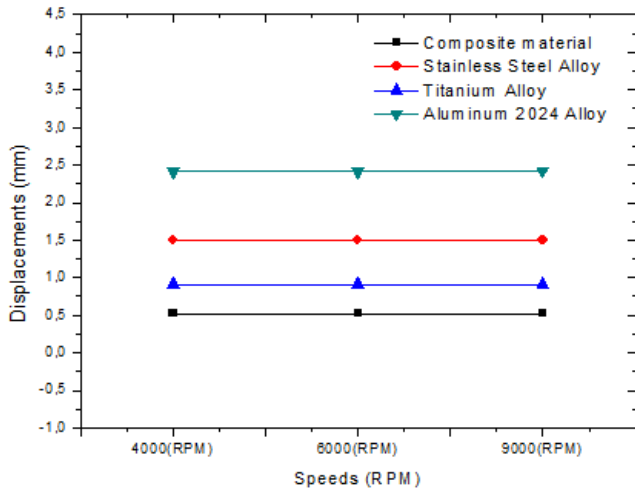


Figure 17. Total displacements induced in turbine blades made of different materials at various speeds

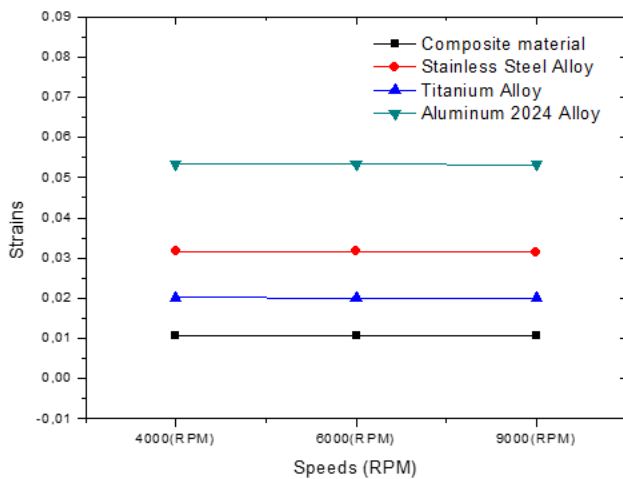


Figure 18. Strains induced in turbine blades made of different materials at various speeds

The Thermomechanical analysis of turbine Blades with different rotational speeds 4000, 6000 and 9000 rpm's by specifying structural and thermal loads with the objective of know the preferred material for the best performance. Based on the results obtained from the Ansys software the graphs, Figure 17 (Total displacement vs Rotation), Figure 18 (Strain vs Rotation) were plotted. The displacement and strains are proportionally increasing with an increase in rotation (RPM). this study it is concluded that the composite material should be used as turbine blade materials in the case of fixed or variable velocity because the displacement and strain is the minimum in the materials used in the comparison.

9. CONCLUSION

The choice of optimized composite material, significantly reduces the deformations along the fin and therefore locally reduces micro cracking causing wear flaking. In order to achieve the desired results, we completed the establishment of a research protocol in a predefined order:

1. A critical study on thermo-mechanical behavior in relation to the wear by flaking of gas turbine blades (problematic) for different materials.

2. A broad literature review on new materials (composites) and technical means to integrate them into the design and manufacture of turbine blades in general. The choice of a couple (reinforcement /matrix) is Carbon / ceramic after an optimization study to choose the optimum composition (fiber volume fraction $v_f=0.4$).
3. Successive studies of simulations carried out on a real geometrical model (blade) of composite materials compared with the same model in super alloys to define essentially the displacements of the same point for the different materials and the local deformations.
4. The obtained results have showed a clear improvement of the fin stiffness and a reduction of the displacement of the extreme point of the blade. The local deformations are reduced. These results allow us to conclude that the cracking by scaling will be reduced significantly.
5. The optimization of a composite material (carbon/ceramic) in the design of turbojet blades has confirmed that the carbon/ceramic torque is very well adapted to an optimum thermo-mechanical operation. Increased stiffness, local reduction of deformations, reduction of micro cracking, and reduction of flaking and therefore increased life time can be achieved.

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NOMENCLATURE

E	Young's modulus of matrix, GPa
E_f	Young's modulus of fiber, GPa
E_L	Elastic modulus in the longitudinal direction, GPa
E_m	Young's modulus of matrix, GPa
$E_{mât}$	Young's modulus of the mast reinforcement, GPa
E_T	Elastic modulus in the transverse direction, GPa
F_a	Axial force N
F_c	Centrifugal force N
F_t	Tangential force N
G_L	Shear modulus in longitudinal direction, GPa
$G_{mât}$	Shear modulus of the mast reinforcement
G_T	Shear modulus transverse direction, GPa
L	Length mm
V_f	Fiber volume fraction
V_m	Matrix volume fraction
α	Coefficient of thermal expansion, $10^{-6}(\text{°C}^{-1})$
α_L	Thermal expansion in the longitudinal direction, $10^{-6}(\text{°C}^{-1})$
α_T	thermal expansion in the Transverse direction, $10^{-6}(\text{°C}^{-1})$
μ	Poisson's ratio
μ_L	Poisson's ratio in the longitudinal direction
$\mu_{mât}$	Poisson's ratio of the mast reinforcement
μ_T	Poisson's ratio in the Transverse direction
ρ	Density [Kg/m^3]
δ	Yield strength