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Fatigue Life Assessment of Unidirectional Fibrous Composite Centrifugal Compressor Impeller Blades Based on FEA

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***Abstract*— Fatigue is the main failure mode of centrifugal compressor impeller. It is subjected to the various cyclic loads such as vibratory and centrifugal loads. This repeated loading and unloading can reduce the life of compressor impeller and blades. In the present research, fatigue analysis of centrifugal compressor impeller is investigated based on FEA. The stress analysis is done and the failure critical region is determined. The stress tensor is extracted at all running time for critical region. The time history of equivalent stress is obtained and the fatigue life is predicted by utilizing post-processing step of the finite element analysis output results. Finally, the obtained finite element results for models made of different materials are compared.**

***Keywords*— Centrifugal compressor impeller, Compressor blades, Fatigue analysis, Fatigue failure, Finite element analysis.**

I. Introduction

The centrifugal compressor is the vital component of gas/steam or oil equipment which uses in the various important industries such as energy, petroleum and chemical engineering industry. There are two general categories for blade failures: a) fatigue and b) creep rupture.

In general, there are different loadings such as machining residual stress, assembly stress, thermal stress, centrifugal stress and fluid stress in operation conditions which influence on the behavior of impeller. The revolving speed of impeller can reach 2-100 Kr/min [1].

It was reported that more than 50% (even 90% in some studies) of the failure in gas turbine or compressor were only due to blading problems [1]. A comparison between different industrial components and their expected life cycles are shown in Figure 1 [2].

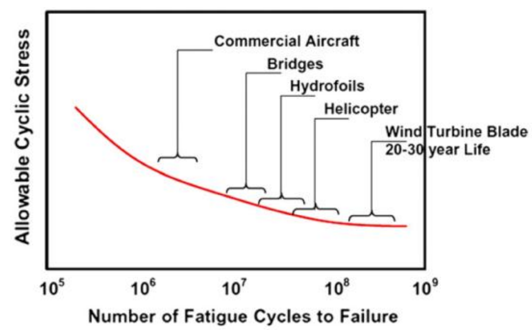

Fig 1. Schematic S-N curve for different industrial components [2]

Many researchers have studied fatigue characteristics of compressor blades. Research results illustrated effectiveness in preventing blade failure and improving compressor performance. Carter has described types of common failures in gas turbine blades such as high temperature, creep, fatigue and corrosion damages [3]. Bhagi et al. have reported a brief review on failure of turbine blades [4].

Fatigue crack propagation and crack growth in gas turbine compressor blades have been studied experimentally. Optical and scanning electron microscopy images have been used to study microstructure and fracture surface of blades [5-8].

Maktouf et al. have predicted multi-axial fatigue life of gas turbine blade under different loading conditions. Several multi-axial fatigue models have been applied as post-processing step of the finite element analysis output results to choose an appropriate fatigue design criterion. They have reported that Dang-Van criterion is predicted the most conservative life [9].

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Liu et al. have predicted fatigue life of healthy [1] and cracked [10] centrifugal compressor blade which is made of FV520B. Poursaeidi et al. have simulated crack growth in a gas turbine compressor blade of model GE-F6 [11]. Witek et al. have investigated fatigue life of compressor blade with foreign object damage and notch on the leading edge. The number of load cycles to crack initiation and crack growth have been predicted by using finite element results for the first mode of resonant vibration of blade [12].

Li et al. have studied fatigue failure of composite blades by using Miner's linear law [2].

Kou et al. have investigated dynamic and fatigue compressor blade characteristics during fluid-structure interaction [13].

The aim of this work is to evaluate fatigue behavior of centrifugal compressor impeller with different materials. To identify this, FV520B and Nickel base alloy are considered as the common materials of the impeller. The carbon/epoxy laminated composite is considered as new material to study impeller behavior. Stress analysis has done under only centrifugal and aerodynamic loads. Fatigue damage and life is predicted by using FEM.

II. Modelling

Full size model of centrifugal compressor impeller is built with SOLIDWORKS software as shown in Figure 2. The impeller is an open impeller with 15 blades. In meshing process, it is important to combine the calculating efficiency and the calculating accuracy. The full sized model of impeller is generated by tetrahedral mesh with initial mesh size of 8 mm. The mesh convergence is studied based on Maximum Von-Misses stress. The results of convergence analysis are reported in Table 1.

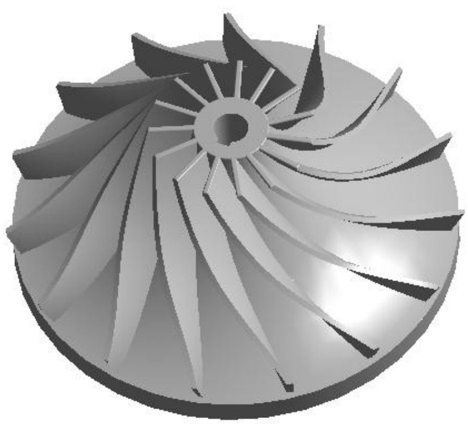

Fig 2. Geometric model of centrifugal compressor impeller with 15 blades

Table 1.
Convergence analysis based on Maximum Von-Misses stress

Analysis No.	Mesh size (mm)	Number of elements	Stress (MPa)	Stress converge (%)
1	8	39141	1041.8	
2	6	83796	955.71	8.619
3	5	141052	874.51	8.732
4	4	266533	846.55	3.240
5	3	634061	840.1	0.764
6	2	2100886	839.98	0.015

It is evident that at least 266,000 elements are required for the convergence the stress converges to 3.2%. The final mesh size of 4mm is selected and mesh model is shown in Figure 3.

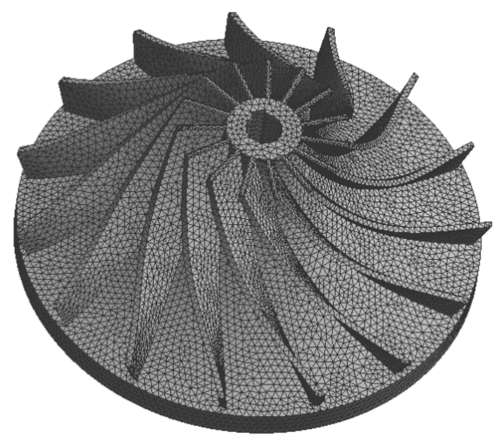

Fig 3. Final mesh model of centrifugal compressor impeller with 15 blades

III. Material Characterization

Three different materials are used to investigate fatigue life of centrifugal compressor impeller and blades. In the first phase, it is assumed that the compressor impeller and blades was made of Nickel base alloy and was manufactured by investment casting method [6]. The chemical composition of compressor blade is reported in Table 2.

EXPLORING RESEARCH AND INNOVATIONS

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Table 2.
Chemical composition of blade made of Nickel based super alloys [6]

Element	C	S	P	Mn	Si	Cr	Ni
Wt%	0.009	0.004	0.004	0.01	0.12	19	67.81
Element	**Mo**	**Ti**	**W**	**Fe**	**Al**	**Co**	
Wt%	6.10	1.56	3.05	0.48	1.73	0.067	

The stress-strain diagram for grain size (ASTM) 5 and Gamma prime size 100 nm with distribution of precipitates one size is illustrated in Figure 4.

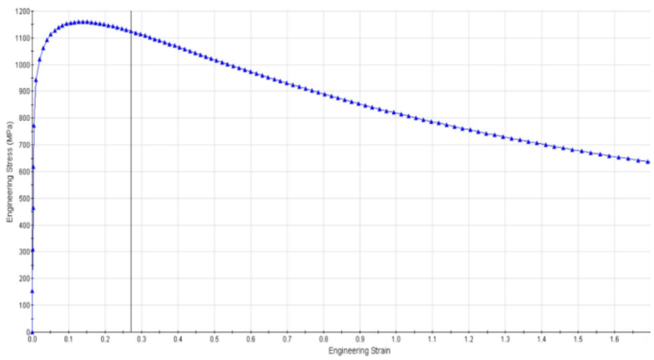

Fig 4. Stress-Strain diagram of Nickel base alloy

From this figure, the mechanical properties are following as: Hardness 31.6 HRC, Young's modulus 211.1 GPa, 0.2% proof and tensile stress are 774.56 and 1170.56 MPa, respectively.

In the second phase, the laminated carbon/epoxy composite is used to study fatigue failure of centrifugal compressor impeller. Carbon fiber As-4 from Hexcel Inc. and epoxy SC-15 made by applied Poleramic Inc. were used as composite structure. The fiber volume fraction of 30% is used to determine composite properties by Micro-Mechanics Model [14-15]. The unidirectional composite mechanical properties are shown in Table 3 [2].

Table 3.
Composite mechanical properties (GPa) [2]

Material	E_{11}	E_{22}	E_{33}	G_{12}	
Carbon fiber	231	15	15	15	
Epoxy	26.2	26.2	26.2	9.17	
Unidirectional composite	87.64	22.84	22.84	14.52	
Material	G_{13}	G_{23}	ϑ_{12}	ϑ_{13}	ϑ_{23}
Carbon fiber	15	7	0.2	0.2	0.2
Epoxy	9.17	9.17	0.35	0.35	0.35
Unidirectional composite	14.52	8.52	0.31	0.31	0.31

IV. LOADING

In operational condition, there are different loadings such as machining residual stress, assembly stress, thermal stress, centrifugal stress and fluid stress which are effect on the behavior of impeller. In this paper, only centrifugal and aerodynamic loads are considered. Based on the results of the previous research, the aerodynamic load can be simplified as uniform pressure (35 KPa) on the suction and the pressure surface respectively. Meanwhile, the centrifugal load is loaded at the spindle with constant angular velocity of 4789 rad/s [1].

V. STRESS ANALYSIS AND VALIDATION OF THE PRESENT SIMULATION

In order to validation of present simulation, the stress analysis is done for centrifugal compressor impeller which is made of FV520B. The Von-Misses stress contour of impeller is shown in Figure 5.

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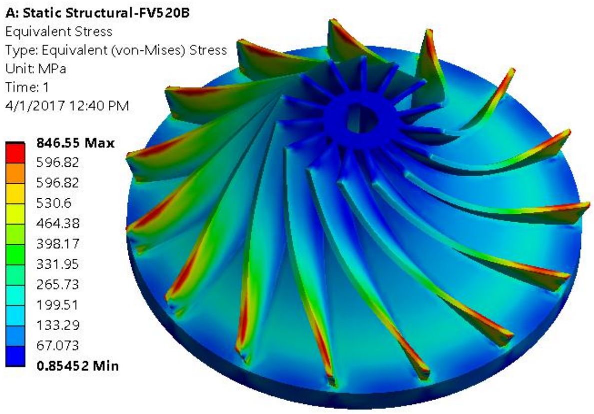
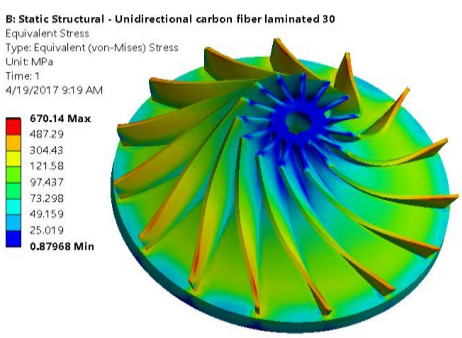
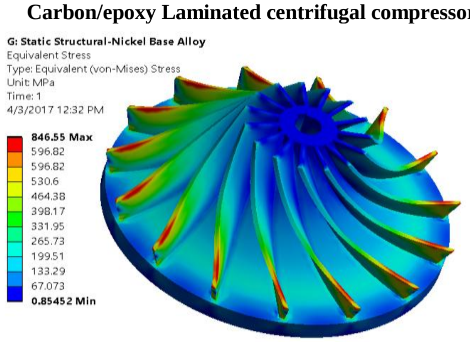


Fig 5. Von-Misses stress contour of FV520B impeller

According to the obtained result, the maximum Von-Misses stress is reported 846.55 MPa that has a good agreement with published results (840 MPa) [1]. After that, the stress analysis is done for base nickel alloy and carbon/epoxy laminated composite to determine the critical failure region. The Von-Misses stress and strain contour for different materials are shown in Figure 6 and Figure 7, respectively.



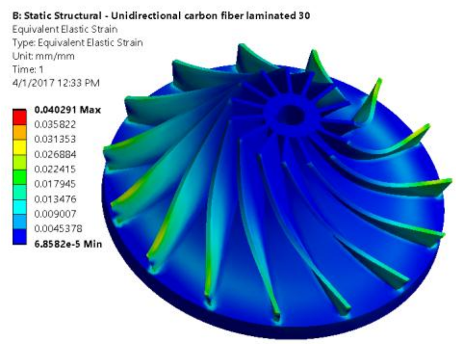
a. Carbon/epoxy Laminated centrifugal compressor impeller



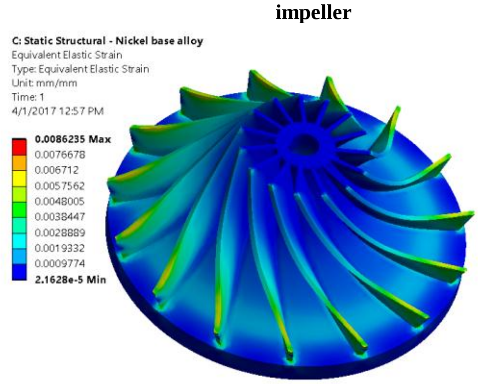
b. Nickel base alloy centrifugal compressor impeller

Fig 6. Equivalent (Von-Misses) stress contour of centrifugal compressor impeller with different materials

The stress concentration regions are at the top of the blades as well as the joints of the blades and the body. The maximum stress in the composite impeller is less than in the impeller made of other materials. However, the equivalent elastic strain value of composite impeller is about eighty and forty percent lower than in the impeller made of Nickel base alloy and FV520B respectively. Thus, it is expected that the fatigue life of composite impeller is more than fatigue life of FV520B and Nickel base alloy impellers.



a. Carbon/epoxy Laminated centrifugal compressor impeller



b. Nickel base alloy centrifugal compressor impeller

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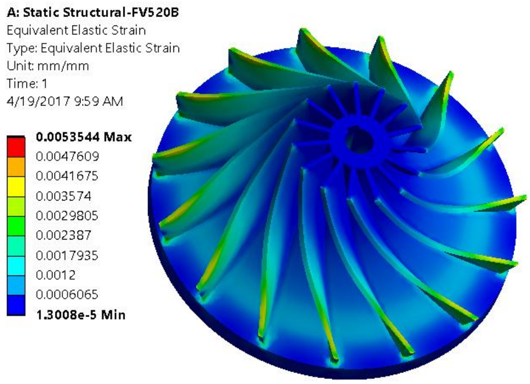


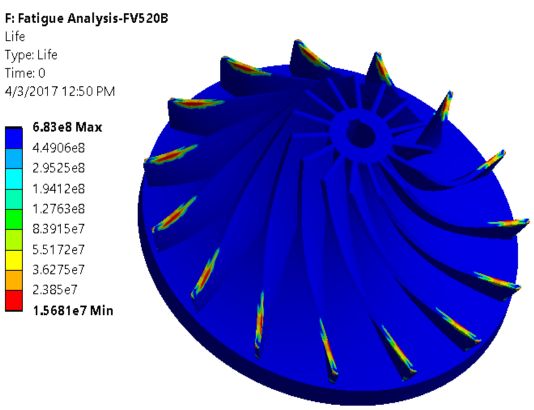
c. FV520B centrifugal compressor impeller

Fig 7. Equivalent (Von-Misses) elastic strain contour of centrifugal compressor impeller with different materials

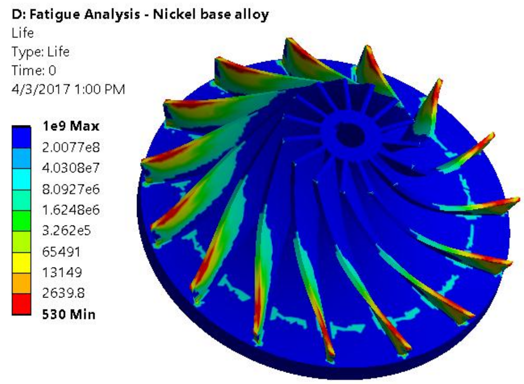
VI. Life Prediction Results And Discussions

Fatigue life of impeller is predicted by utilizing post-processing step of the finite element analysis output results [16-17]. The reverse stress is considered as cyclic loading. The fatigue life contour of impeller with different materials are shown in Figure 8.

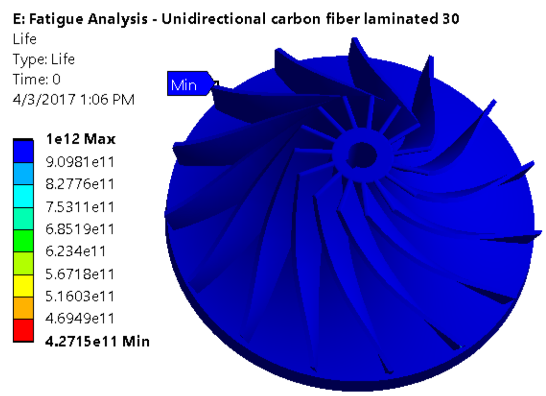
According to the FEM results, the fatigue life of centrifugal compressor impeller under centrifugal and aerodynamic loads for different materials are reported in Table 4.



a) FV520B



b) Nickel base alloy



c) U-D carbon fiber laminated

Fig 8. Fatigue life of centrifugal compressor impeller with different materials

Table 4.
Fatigue results of impeller

Material Name	**Fatigue life (Cycle)**
FV520B	**1.5681e7**
Nickel base alloy	**530**
Fiber/epoxy laminated composite	**4.2715e11**

VII. Conclusion

In this study the stress analysis was performed to investigate fatigue life of centrifugal compressor impeller.

Different material groups were used to choose the most appropriate material for compressor impeller and blades which were faced to various loading conditions. In the present research, only centrifugal and aerodynamic loads are considered. Fatigue life is predicted by applying post-processing step of the FEM results. During the work preparation the following conclusions were formulated:

a) The stress concentration regions are at the top of the blades as well as the joints of the blades and the body.
b) The maximum stress in the composite impeller is less than in the impeller made of other materials. However, the equivalent elastic strain value of composite impeller is about eighty and forty percent lower than in the impeller made of Nickel base alloy and FV520B respectively.
c) According to the figure 1, the fatigue life of impeller with FV520B material is estimated in the acceptable area. But it is not acceptable for Nickel base alloy. Therefore, the nickel base alloy is not suitable for use in the above working conditions.
d) The fatigue life of composite impeller is estimated more than FV520B material. It is shown that the composite material is more appropriate to use for impeller manufacturing.

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