ACTA TECHNICA JAURINENSIS
Vol. 16, No. 4, pp. 152-157, 2023
10.14513/actatechjaur.00714

Research Article

Structural Integrity of Turbine Stator Blades Using Different Super Alloys with Internal Cooling at Fluid Temperature Range of 600 K – 700 K

Olumide Towoju[1,*], Samuel Enochoghene[2], John Adeyemi[1]

[1]Mechanical Engineering Department, Lead City University
Ibadan, 200255, Nigeria
[2]Electronic and Electrical Engineering Department, Lead City University
Ibadan, 200255, Nigeria
*e-mail: olumide.towoju@lcu.edu.ng

Submitted: 13/09/2023 Accepted: 14/11/2023 Published online: 27/11/2023

Abstract: The importance of turbines in power generation cannot be overstated. While the failure in stationary plants can lead to downtime and high repair costs, its failure in mobile plants like the jet engines can be catastrophic with attendant loss of lives. Hence, by all possible means, the prevention of turbine failure is a necessity, and a very good means of doing this is with the use of super-alloys. Super-alloys are tailored to withstand the demands of turbine operations especially stress and elevated temperature and pressure. The blades are thus, manufactured from super-alloys, and of prominence are the Nickel-based super-alloys. The performance of five different super-alloys: (DS) GTD 111, Ti-6Al-4V, Inconel 718, CMSX-4, and Nimonic 80A was simulated using COMSOL MultiPhysics 5.5 at cooling air temperature range of 600 K – 700 K. The mode of cooling employed in the study is only internal cooling. With the developed stress percentage of the yield stress value and the stator blade displacement at the operating conditions as the criteria of performance, super-alloy Ti-6Al-4V faired as the best material for the stator blade.

Keywords: blade Displacement; developed stress; failure; yield stress

I. Introduction

The need for efficient turbines in the engineering world is enormous, as it is a good means of power generation in both stationary plants and jet engines. The need to subject a turbine to very high temperatures and pressure at operation periods places a high burden on its designers in the selection of appropriate materials and as such, turbine blades that are in constant contact with high temperature combustion gases are made from high temperature resistant materials [1]. The very high temperature demand of turbine blades has broadly limited its production materials to Nickel-based super alloys [2, 3] and some other elements like Rhenium and Titanium. To ensure the prevention of turbine blades failure due to very high temperatures, effective cooling is also, a necessity [1, 4]. While it is difficult to attribute a single cause for the reason for turbine failures, the indicators are more glaring at the hot sections and thus, we can attribute it to be direct and indirect consequences of the very high temperatures [2, 5-6].

It is undisputable that the thermal efficiency of combustion engines is a function of their maximum temperature, and thus, optimizing the performance of turbines is dependent on attainable maximum temperature while putting the metallurgical limit into perspective. A situation that is helped with efficient cooling. However, if not well managed, this can be a recipe for failure [1]. This is not just required for turbines, proper cooling is also required in braking systems to avoid brake fade [7]. One of the means of turbine blades cooling is “internal cooling’, others are film and coated cooling. The temperature variation of internal cooling air affects the blades temperature values, such that the lower the temperature the more beneficial it is in terms of keeping the blades temperature below the metallurgical limit [1]. However, this have a negative impact on other its yield, hence necessitating the need for an optimized temperature value to ensure optimal results [1].

Studies on the use of (DS) GTD 111 as a stator blade material using only internal cooling while adopting suitable approximations and assumptions resulted in a cooling air temperature of 660 K for optimized performance [1]. While (DS) GTD 111 is one of the numerous Nickel-based super alloys used in turbine blade manufacture, others exist and there is a possibility of improved performance with their usage. The breakthrough for the production of durable turbine blade materials were brought about by the development of the directional solidification (DS) and the single crystal (SC) method of production [8]. These super alloys have excellent mechanical properties at elevated temperatures that are required for optimal performance of turbines [9].

Titanium-6Al-4V is have good properties qualifying it for use as a turbine blade material such as high strength, high temperature and corrosion resistance, and asides form their applications for turbine blades, they are also good for use in nuclear plants [10-12]. Inconel 718 is one of the excellent super alloys for the manufacture of turbines due to superb tensile strength, fatigue strength, and degree of creep rupture at high temperatures, asides the ease of formability and weldability [9]. CMSX-4 is a single crystal Nickel-based super alloy and finds application in turbine blades because of its excellent properties like superb stress-rupture resistance and corrosion resistance [13]. CMSX-10 is a third-generation super alloy [8] purposely designed for use in turbine blade applications and is a produced using the single crystal technology.

Nimonic 80A and Nimonic 263 are Nickel-based super alloys that finds application in the manufacture of turbine parts [9]. They have excellent oxidation and corrosion resistance even at elevated temperatures, and good tensile and creep-rupture properties. Nimonic 263 provides improved proof stress and creep strength [14-15], and it offers better ductility in welded assemblies over Nimonic 80A.

This study is committed to exploring the outcome of using other materials like Ti-6Al-4V, Inconel 718, CMSX-4, and Nimonic 80A as the stator blade material to determine the optimized cooling air temperature.

II. Methodology

The heat transfer, developed stress, and structural displacement of the turbine stator was determined numerically using the heat transfer and the structural mechanics modules available in COMSOL MultiPhysics 5.5 Version.

The heat transfer in the stator is gotten using governing equation:

$$\rho C_p \boldsymbol{u}.\nabla T + \nabla.\boldsymbol{q} = Q + Q_d \quad (1)$$

This equation is a simplified form of the general equation of heat transfer in solids with the assumption of steady state temperature over time. The equation applies only to the heat transfer in the stator, and the effect of stresses are factored in by coupling of the equations of motion in the MultiPhysics module.

$$\boldsymbol{q} = \text{heat conduction} = -k\nabla T \quad (2)$$

C_p − heat capacity, Q − heat transfer, u − velocity of fluid, and Q_d − *thermoelastic damping*

The heat flux is gotten using the expression;

$$q_0 = h(T_e - T) \quad (3)$$

The boundary condition here is the specified heat flux, h, is the convective heat transfer coefficient and represents all the physics occurring between the boundary and "far away."

The governing equation derived from the equation of motion based on virtual work is used to solve for the stress developed and the structural displacement:

$$0 = \nabla.S + \boldsymbol{F}v \quad (4)$$

Fv − volume force vector, ∇. S − stress divergence, S − 2nd Piola − Kirchoff stress is as expressed thus:

$$S = S_{ad} + C{:}\in_{el} \quad (5)$$

C − Viscous damp $= C(E, v)$ *and* $\in = \frac{1}{2}[\nabla u^T + \nabla u]$

The stator geometry is akin to that of NASA power turbine, the study employed a free tetrahedral mesh type with minimum and maximum size corresponding to 0.00228 m and 0.0182 m. the resolution of the narrow regions was set to 0.6, the curvature factor to 0.5, and the maximum element growth rate to 1.45. The generated mesh on the turbine stator blade for CMSX -4 is depicted in **Fig. 1**

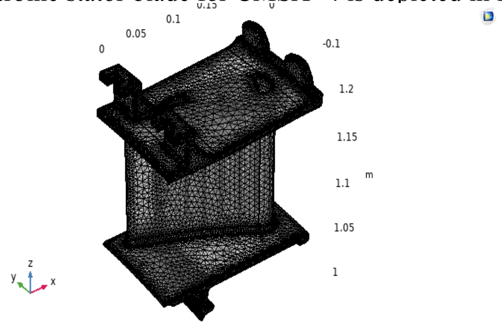

***Figure 1**. Meshing of Turbine Stator (CMSX-4)*

The fluid employed for the internal cooling was taking to be air, and some of the parameters used are depicted in **Table 1**.

Some of the assumptions made in simplifying the study are as enumerated:

1. Cooling is only internally by the flow of the air.
2. The combustion gas temperature is 1100 K.

Table 1. *Cooling air study parameters*

Parameter	***Values***
Free stream velocity at platform walls	350 m/s
Stator pressure side gas velocity	300 m/s
Stator suction side gas velocity	450 m/s
Working temperature	900 K
Working pressure	30 bar

3. The adopted Mach number for the pressure and suction sides are 0.45 and 0.7 respectively.
4. The pressure and suction sides of the duct are flat plates.
5. An average Nusselt number correlation was used for the calculation of the heat transfer coefficient. This is possible due to the cooling duct geometry not including the rib details.
6. The turbine has a working temperature of 900 K and a heat transfer coefficient of 25 W/ (m^2. K)

The corresponding Poisson's ratio of the different materials used for the stator blade is as presented in **Table 2**.

Table 2*. Poisson's Ratio values of the studied materials*

(DS) GTD 111	***Ti-6Al-4V***	***Inconel 718***	***CMSX-4***	***Nimonic 80A***
0.33 [1]	0.34 [12]	0.29 [16]	0.39 [13]	0.3 [17]

The air values of heat capacity, Prandtl number, and viscosity at the studied temperature range were determined from literature [1].

III. Results and Discussions

Bearing in mind that the value of the developed stress must be lesser than the material yield stress at the working temperature to prevent failure, the yield stress values for the different utilized blade stator materials is as depicted in **Table 3**.

Table 3*. Yield Strength at 923 K (MPa)*

(DS) GTD 111	***Ti-6Al-4V***	***Inconel 718***	***CMSX-4***	***Nimonic 80A***
645.62	350 [10]	980	1060 [12]	710

The behavior of the stator blade resulting from the modelling with COMSOL MultiPhysics 5.5 for the selected super alloys are presented in figures. These are plots of blade displacement (mm), developed stress (MPa), yield stress value (MPa) at 923 K, and cooling air temperature (K). **Fig. 2, 3, 4, 5**, and **6** present the results for the selected super-alloys; (DS) GTD 111, Ti-6Al-4V, Inconel 718, CMSX-4, and Nimonic 80A respectively.

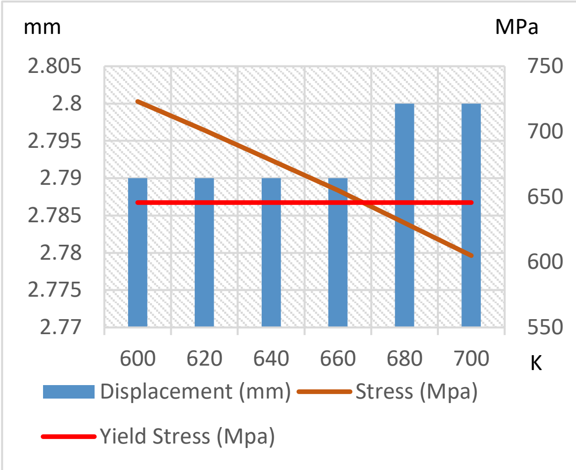

Figure 2*. Stress – Displacement Plots for (DS) GTD111*

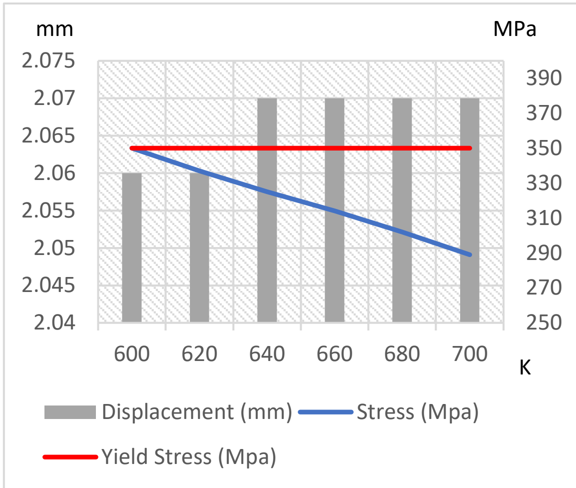

Figure 3*. Stress – Displacement Plots for Ti-6Al-4V*

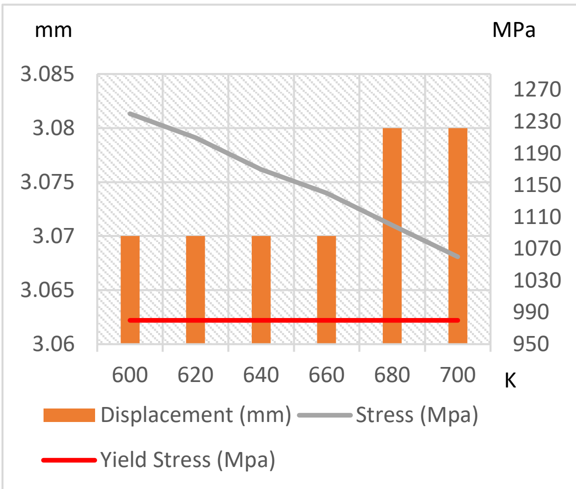

Figure 4*. Stress – Displacement Plots for Inconel 718*

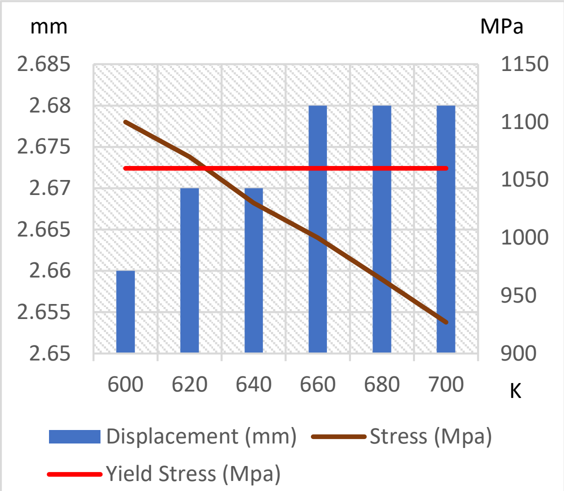

***Figure 5**. Stress – Displacement Plot for CMSX-4*

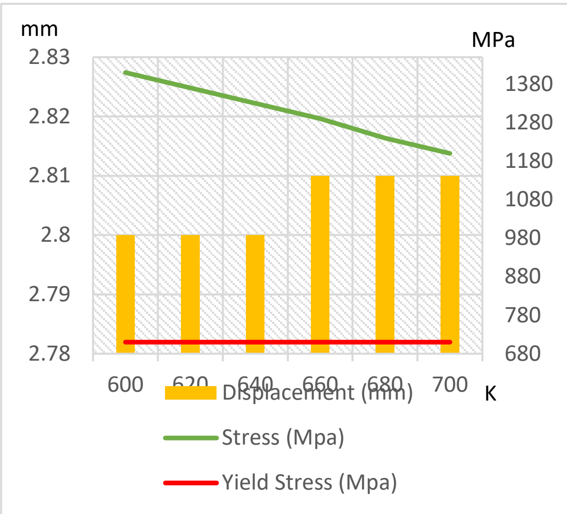

***Figure 6**. Stress – Displacement Plots for Nimonic 80A*

The developed stress in the stator blade increases with the decrease in cooling air temperature and the displacement of the stator blade decreases with decreasing cooling air temperature irrespective of the material used. While as little as possible blade displacement is desirable and is favoured with low cooling air temperature values, which in turn ensures that the material operates below the metallurgical limit, the same does not apply to the developed stress. Exceeding the yield stress at the normal working condition will lead to structural failure, and thus, there must be an optimization of the cooling air temperature to accommodate all the required features.

The developed stress for super-alloys; (DS) GTD 111, Ti-6Al-4V, and CMSX-4 will at a point be below the material yield stress for the considered cooling air temperature range, while for the super-alloys; Inconel 718 and Nimonic 80A this was not the case. Super-alloy Ti-6Al-4V will allow for the least value of cooling air temperature of the three that qualifies for the range 600 K to 700 K, followed by CMSX-4.

It is possible for the developed stress values to be lesser than the material yield stress for Inconel 718 and Nimonic 80A with an increase in the cooling air temperature; however, this will signify increased stator blade displacement and average temperature. From the data provided in Figure 4, the gradient of the line is 1.8 ($m = \frac{y_2 - y_1}{x_2 - x_1}$) and using this to predict the cooling air temperature at which the developed stress will be equal to the yield stress gives the value 744.44 K.

This implies that if the cooling air temperature is made to be ≥ 744.44 K, the value of the developed stress will be equal to or lesser than the yield stress of Inconel 718. And it is only at cooling air temperature values above this value that there will be a certainty of prevention of the blade deformation and failure taking note of only internal cooling.

To determine the most suitable super-alloy for application as a turbine stator blade when cooling mode is only internal, this study calculates the cooling air temperature that leads to a developed stress value that is 98% of its yield stress by interpolation. The presentation of the result is in **Fig 7**.

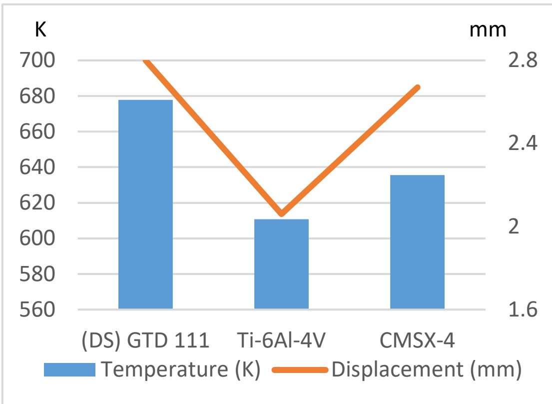

***Figure 7**. Performance Comparison of Some Super-Alloys using Internal Cooling*

Super-alloy Ti-6Al-4V as the stator blade material faired as the best due to the least value of displacement while allowing for the least cooling air temperature of the three. This is an indication that while being subjected to the operating conditions, Ti-6Al-4V super-alloy will experience the least of thermal fatigue stress of the considered materials. This is consistent with its wide application in the aerospace industry providing the required properties even at elevated temperatures.

Super-alloy CMSX-4 and (DS) GTD 111 also demonstrated better performance than the remaining two considered super-alloys and echoed the significance of the direct solidified and single crystal manufacturing technology.

IV. Conclusion

The study employed only internal cooling as the cooling means of the turbine stator material while neglecting film and coated cooling. Based on the studies on five different super-alloys: (DS) GTD 111, Ti-6Al-4V, Inconel 718, CMSX-4, and Nimonic 80A, the following deductions were made:

1. The developed stress of the super-alloys decreased with an increase in cooling air temperature, while the opposite was the case for the stator blade displacement.
2. Super-alloys (DS) GTD 111, Ti-6Al-4V, and CMSX-4 have a developed stress value lower than the yield stress at the studied cooling air temperature range.
3. Super-alloy Ti-6Al-4V showed the least stator blade displacement at 98% developed stress of the corresponding yield stress value of the studied super-alloys.

Acknowledgement

We appreciate Lead City University, Nigeria for providing the enabling environment for the conduct of this study.

AUTHOR CONTRIBUTIONS

O. A. Towoju: Conceptualization, Modelling, Theoretical analysis, Writing.

S. O. Enochoghene: Review and editing.

J. A. Adeyemi: Review and editing.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ORCID

Olumide Towoju https://orcid.org/0000-0001-8504-2952

Samuel Enochoghene https://orcid.org/0000-0001-8751-4351

References

[1] O. Towoju, Impact of cooling fluid temperature on the structural integrity of gas turbine stator blades, Engineering and Technology Journal, 41 (7) (2023), pp 1-9. http://doi.org/10.30684/etj.2023.138881.1409.

[2] R. Wang, B. Zhang, D. Hu, K. Jiang, H. Liu, J. Mao, et al., Thermomechanical fatigue experiment and failure analysis on a Nickel-based superalloy turbine blade, Engineering Failure Analysis, 102, (2019), pp. 35–45.

[3] P. Puspitasari, A. Andoko, and P. Kurniawan, Failure analysis of a gas turbine blade: A review, IOP Conf. Series: Materials Science and Engineering, 1034 012156, (2021), pp. 1-9. https://doi.org/10.1088/1757-899X/1034/1/012156

[4] A. M. Mirhosseini, S. A. Nazari, A. M. Pour, S. E. Haghighi, and M. Zareh, Failure analysis of first stage nozzle in a heavy-duty gas turbine, Engineering Failure Analysis, Vol. 109:104303, (2020).

[5] R. K. Mishra, N. Vaishakhi, and R. R. Bhatt, Thermo-mechanical fatigue failure of a low-pressure turbine blade in a turbofan engine, J Fail Anal and Preven, 18 (2) (2018), pp.233–40.

[6] H. Kazempour-Liasi, A. Shafiei, and Z. Lalegani, Failure analysis of first and second stage gas turbine blades, J Fail Anal and Preven, 19 (6) (2019), pp. 1673–82.

[7] O. A. Towoju. Braking Pattern Impact on Brake Fade in an Automobile Brake System” Journal of Engineering Sciences. 6 (2) 2019, pp. E11-E16. https://doi.org/10.21272/jes.2019.6(2).e2

[8] B. C. Wilson, E. R. Cutler, and G. E. Fuchs, Effect of solidification parameters on the microstructures and properties of CMSX-10, Materials Science and Engineering: A, Vol. 479 (1-2) (2008), pp. 356-364. https://doi.org/10.1016/j.msea.2007.07.030

[9] C. Korkmaz and O. Gul, Analysis of the mechanical properties of Inconel 718, 5th International conference on Applied Engineering and Natural Sciences, All Science Proceedings, (2023), pp. 673-678. http://as-proceeding.com/

[10] I. P. Semenova, M. K. Smyslova, K. S. Selivanov et al., Enhanced fatigue properties of Ti-6Al-4V alloy turbine blades via formation of ultra-fine grained structure and ion implantation of surface, IOP Cof. Ser.: Mater. Sci. Eng., 194,012035, (2017). https://doi.org/10.1088/1757-899X/194/1/012035

[11] S. Ivanov, M. Gushchina, A. Artinov, et al.. Effect of elevated temperatures on the mechanical properties of a direct laser deposited Ti-6Al-4V, Materials (Basel), 14 (21):6432, (2021).

[12] D. Tuner, M. Gungorurler, H. Havitcioglu, and Y. Arman, Investigation of effective coating of the ti-6al-4v alloy and 316l stainless steel with graphene or carbon nanotubes with finite element methods, Journal of Materials Research and Technology, 9 (6) (2020), pp. 15880-15893. https://doi.org/10.1016/j.mrt.2020.11.052

[13] T. Wang. H. Zhang, C. Liu, et al., Effect of tensile behavior, fracture morphology and deformation mechanisms of nickel-based single crystal CMSX-4, Journal of Alloys and Compounds, 912 (2022). https://doi.org/10.1016/j.jallcom.2022.165175

[14] A. Di Gianfrancesco. Chapter 17 – Alloy 263. Materials for Ultra-Supercritical and Advanced Ultra-Supercritical Power Plants, Eds: A. Di Gianfrancesco. Woodhead Publishing, (2017), pp. 571-599. https://doi.org/10.1016/B978-0-08-100552-1.00017-8

[15] J. Javad, K. R. V. Rajulapati, N. Eswaraprasad, K. and B. S. Rao., "Effect of temperature on tensile flow behaviour of Nimonic C-263 alloy" Materials Today: Proceedings, 5 (2018), pp. 5475–5480.

[16] S. Metals, "Inconel alloy 718", Publication number SMC-045, Special Metals Corporation, (2007).

[17] B. Wilthan, R. Tanzer, W. Schutzenhofer, and G. Pottlacher, Thermophysical properties of ni-based alloy Nimonic 80A up to 2400 K", Thermochimica Acta, 465 (1-2) (2007), pp. 83-87. https://doi.org/10.1016/j.tca.2007.09.006