Selection of High Performance Alloy for Gas Turbine Blade Using Multiphysics Analysis

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ABSTRACT:
With the extensive increase in the utilization of energy resources in the modern era, the need of energy extraction from various resources has pronounced in recent years. Thus comprehensive efforts have been made around the globe in the technological development of turbo machines where means of energy extraction is energized fluids. This development led the aviation industry to power boost due to better performing engines. Meanwhile, the structural conformability requirements relative to the functional requirements have also increased with the advent of newer, better performing materials. Thus there is a need to study the material behavior and its usage with the idea of selecting the best possible material for its application.

In this work a gas turbine blade of a small turbofan engine, where geometry and aerodynamic data was available, was analyzed for its structural behavior in the proposed mission envelope, where the engine turbine is subjected to high thermal, inertial and aerodynamic loads. Multiphysics Finite Element (FE) linear stress analysis was carried out on the turbine blade. The results revealed the upper limit of Ultimate Tensile Strength (UTS) for the blade. Based on the limiting factor, high performance alloys were selected from the literature. The two most recommended alloy categories for gas turbine blades are *NIMONIC* and *INCONEL* from where total of 21 types of *INCONEL* alloys and 12 of *NIMONIC* alloys, available on commercial bases, were analyzed individually to meet the structural requirements. After applying selection criteria, four alloys were finalized from *NIMONIC* and *INCONEL* alloys for further analysis. On the basis of stress-strain behavior of finalized alloys, the Multiphysics FE nonlinear stress analysis was then carried out for the selection of the individual alloy by imposing a restriction of Ultimate Factor of Safety (UFOS) of 1.33 and yield strength. Final selection is made keeping in view other factors like manufacturability and workability in due consideration.

1. INTRODUCTION

The aim of turbine in an air breathing engine is to extract energy from energized fluid (high temperature air). It is true that turbine is designed based on the principles of aerodynamics and propulsion but the physical existence and operation of turbine is very much dependent on the material selected for its manufacturing. Usually gas turbines are manufactured with high temperature resistant materials, for example Inconel alloys, Nimonic alloys, etc. These alloys are Nickel based and can be precipitation hardened, due to which these material retain their strength even at high temperatures. Also some of them are creep and corrosion resistant at elevated thermal conditions.

Typically the turbine blades for high performance gas turbine are designed to avoid failure of material during extended high temperature operation. The allowable stress level will depend strongly on the operating temperature and may be specified as a failure limit (mostly yield strength). It is quite common to see materials compared on the results of measurement of stress to see failure or rupture.

Immarigeon [1] has done a comparative study to specify materials for turbine keeping strength to weight ratio in due consideration. Singh, M. and G. Lucas [2] has provided a detailed literature review for design of turbine blade for industrial steam turbines. Boyce [3] has discussed compiled the problems in gas turbine industry in general. Glenny, Northwood, and Burwood-Smith [4] have provided data of materials along with their recommendations for the development of turbine blade. Also Special Metal Corp. [5] has provided information of materials recommended for manufacturing of turbine. Similarly Meetham et al. [6] has discussed materials which can withstand high temperature conditions.

In this effort we have tried to select best suitable alloy for a particular application of the turbine using computational modeling technique using ANSYS® Multiphysics package based on FE methods was used for analyses purposes [7, 8, 9].

2. SELECTION METHODOLOGY

A selection plan as shown in (Figure 1) was developed to select the best suitable material for turbine manufacturing. This was a two-stage process, where initial screening has to be done

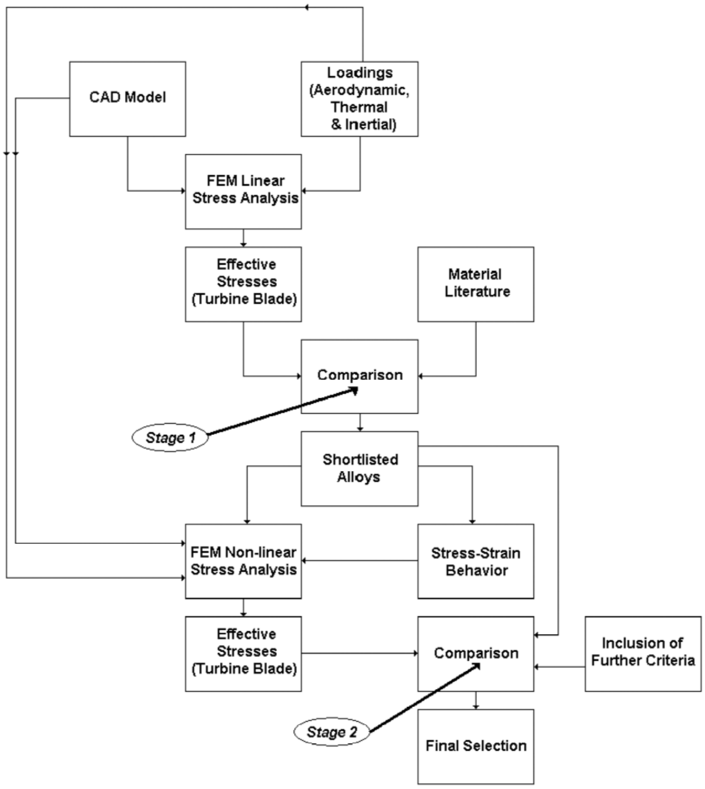

Figure 1: Roadmap of Selection Methodology

in first stage based on linear stress analysis results and final screening has to be done in second stage on the basis of non-linear stress analysis results. In the end, final selection has to be done on the basis of criteria keeping in view the material's mechanical properties and manufacturability.

3. MULTIPHYSICS MODELING & APPLIED LOADS AND CONSTRAINTS

For Multiphysics FE analyses, CAD geometry was built in Pro-E CAD software [10] as per design recommendations of aero-propulsion experts shown in (Figure 2). This geometry was imported into ANSYS® modeling environment by converting CAD file into IGES format [11]. Additional trimming was done in ANSYS® modeling environment. Finite element model was built using suitable element types according to requirement of analysis. Mesh sensitivity analysis was carried out, to have the mesh with an optimum number of nodes because an optimized mesh is capable of giving accurate results with minimum utilization of computational resources, which actually saves time.

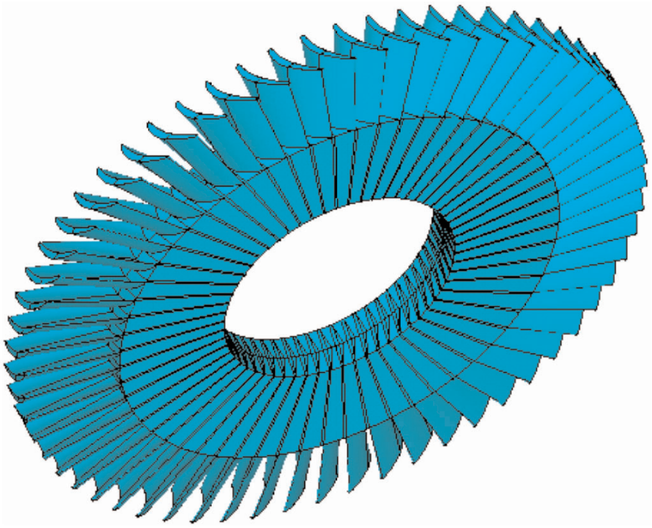

Figure 2: CAD Model of Turbine

To run Multiphysics FE analysis [12] constraints are also required to be defined. So keeping in view original conditions, constraints were applied on the Multiphysics FE model of turbine blade. All nodes at *blade-hub joint* as shown in (Figure 3) were constraint in x-direction except corner nodes, which were constraint in y-axis and z-axis as well as shown in (Figure 4). These constraints were selected on the basis of experiments, carried to find out Boundary Conditions (BC) suitable to take thermal loads along with other aerodynamic and inertial loads without showing any rigid body motion.

Initially Mechanical properties of *Inconel 718* were taken for analyses of the turbine [5].

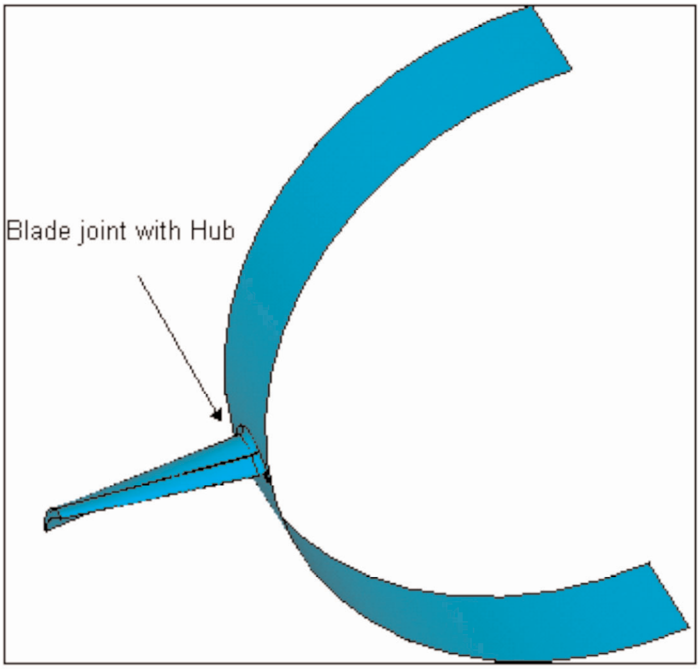

Figure 3: Illustration of Blade Hub Joint

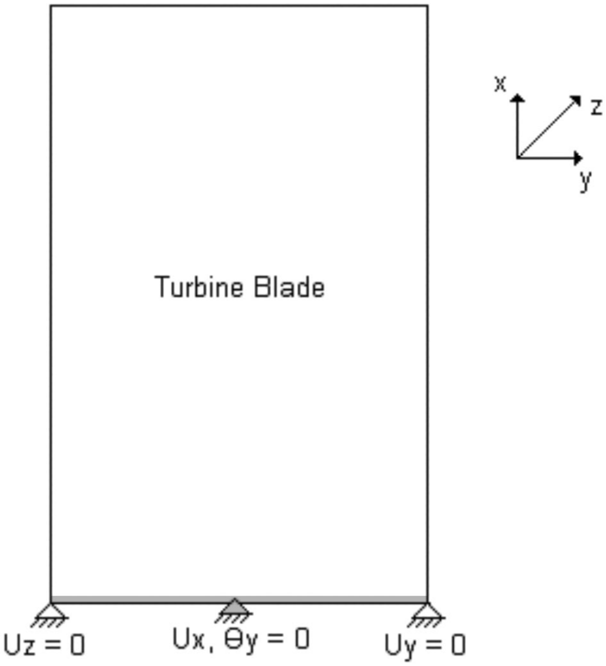

Figure 4: Application of Constraints

5. LINEAR STRESS ANALYSIS

Linear analysis was performed, keeping in view the advantages and limitations of such an analysis. As far as advantages are concerned, much generalized inputs are required for defining a material model. Also computational time for linear analysis is far lesser than non-linear analysis. Results of linear analysis are accurate up to a *proportional limit*. Other than material mechanical properties, finite element analysis also requires meshed model with loads and constraints specified at correct nodes. Care is to be taken that loads or constraints must be applied correctly otherwise results may deviate.

Solid model of the turbine blade was meshed with *Solid 45 Brick 8 Node* element type (Figure 5). Loads and operating conditions of the turbine were applied as per the specification of the aero-propulsion experts (Table 1). Aerodynamic load (Pressure difference on lower and upper surface of blade) was applied normal to inner blade surface, thermal load (temperature difference) was applied throughout the solid blade and inertial load (centrifugal force due to rotation) was applied as body load. Mechanical properties (Young's modulus, Poisson ratio and Coefficient of thermal expansion) of high performance alloy Inconel 718 were used for linear stress analysis.

Table 1: Operating Conditions of Turbine

Maximum Pressure	0.5745 MPa
Maximum Temperature	1056.55 K
Operating RPM (Inertia)	32200 RPM

6. LINEAR STRESS ANALYSIS RESULTS

Linear analysis showed no significant variations in results by varying young modulus. Also results showed higher value of stresses than the actual values. Effective (Von-Mises) stress [13] contour plot was taken as output of the analysis (Figure 6). Maximum value of effective stress was taken for comparative study, as discussed ahead.

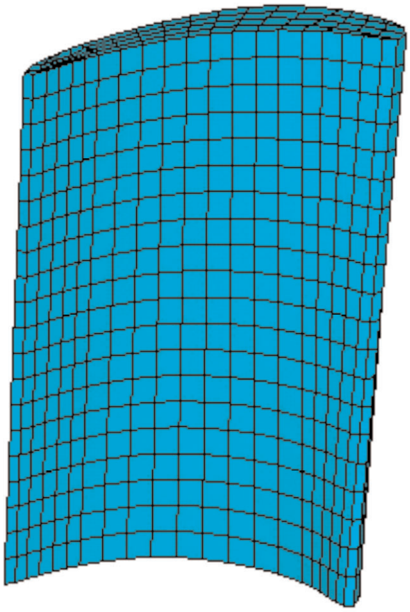

Figure 5: Multiphysics FE Model of Turbine Blade

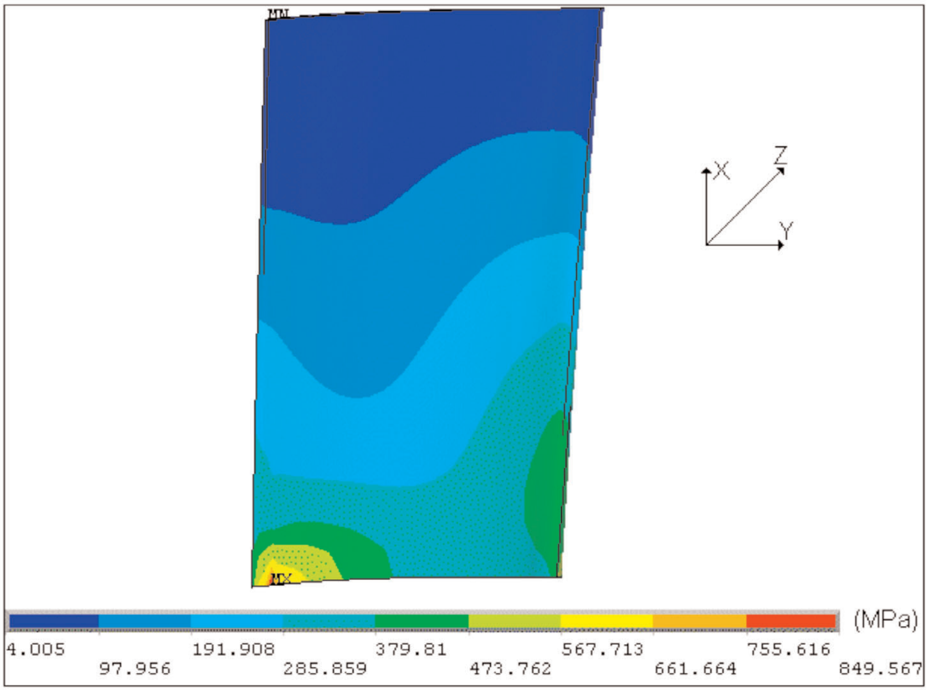

Figure 6: (Von-Mises) Effective Stress Contour Plot (MPa)

7. STAGE 1 SELECTION

Material literature was searched to find a suitable material for manufacturing the turbine blade. The search ended up with finding a material handbook [5]. This material handbook specifies the mechanical properties of high performance alloys that are temperature resistant and recommended to be used for turbine blades. From this source, 21 types of Inconel alloys and 12 types of Nimonic alloys were taken for initial comparison (Table 2). An initial comparison criterion was set as the UTS of materials. Materials passed the criterion were selected for non-linear analysis. As we have the idea that obtained value of maximum stress is higher than actual value, so to be conservative in approach, materials having even lesser value of UTS than maximum value of effective stress obtained were marginally accepted for further analysis.

8. NON-LINEAR STRESS ANALYSIS

Non-linear analysis is material specific where all inputs as specified for linear analysis remain the same except non-linear analysis requires stress-strain data of specific materials to evaluate the stresses. So, based on data available [5] stress-strain data was taken and used to perform non-linear stress analysis.

For this sort of analysis, a solid turbine blade was meshed with *Solid 186 Brick 20 Node* element type (Figure 5). This element type was selected to include geometric non-linearity in consideration which was not considered in earlier analysis.

Table 2: Initial Comparison

Alloy Type	**Ultimate Tensile Strength at 1050 K (MPa)**	**Maximum Effective Stress (MPa)**	**Screened Alloys**
Inconel 600	180	850	X
Inconel 601	230	850	X
Inconel 601 GC	220	850	X
Inconel 617	410	850	X
Inconel 622	390	850	X
Inconel 625	440	850	X
Inconel 625 LCF	440	850	X
Inconel 686	530	850	X
Inconel 690	300	850	X
Inconel 706	590	850	X
Inconel 718	730	850	Marginally Acceptable
Inconel 725	560	850	X
Inconel X-750	580	850	X
Inconel 751	670	850	X
Inconel MA 754	300	850	X
Inconel MA 758	400	850	X
Inconel 783	410	850	X
Inconel C-276	480	850	X
Inconel G-3	390	850	X
Inconel HX	400	850	X
Inconel 050	250	850	X
Nimonic 75	240	850	X
Nimonic 80A	690	850	X
Nimonic 81	480	850	X
Nimonic 86	390	850	X
Nimonic 90	720	850	Marginally Acceptable
Nimonic 105	856	850	Acceptable
Nimonic 115	925	850	Acceptable
Nimonic 263	580	850	X
Nimonic 901	690	850	X
Nimonic PE 11	680	850	X
Nimonic PE 16	390	850	X
Nimonic PK 33	660	850	X

9. NON-LINEAR STRESS ANALYSIS RESULTS

Non-linear analysis result are very much dependent on material mechanical properties that's why stress results of non-linear analysis are accurate even beyond proportional limit. Effective stresses contour plots for screened materials are shown (Figure 7). Maximum value of stress for each specific material is taken for comparison.

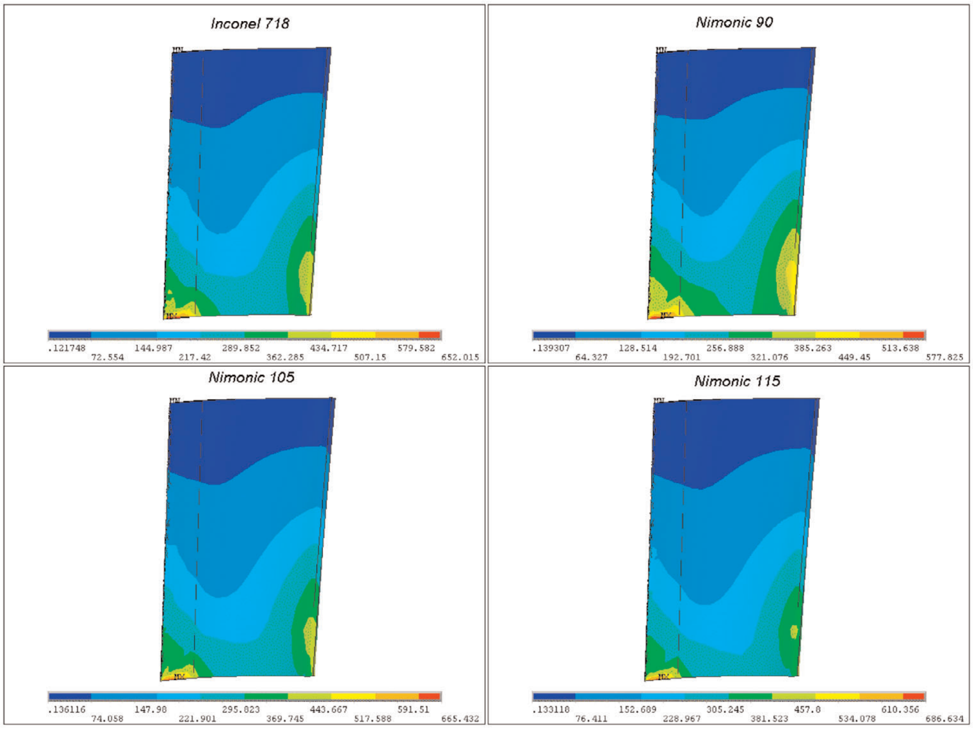

Figure 7: Non-Linear Analysis Results (Effective Stress Contour Plots)

10. STAGE 2 COMPARISON:

Two different criteria were set to select best suited material for manufacturing of turbine. These include *Ultimate FOS* (factor of safety) equal to 1.33 and yield strength. Value of maximum effective stresses as per non-linear analysis was compared with Ultimate FOS and yield strength (Table 3). On the basis of comparison, best suited material was selected.

Table 3: Stage 2 Comparison

Screened Alloys	UTS at 1050K (MPa)	Maximum Stress (MPa)	UFOS	Yield Strength (MPa)	Selected Alloy
Inconel 718	730	652	1.12	689	X
Nimonic 90	720	577	1.25	598	X
Nimonic 105	856	665	1.29	718	X
Nimonic 115	925	686	1.35	750	Accepted

11. FINAL SELECTION

Nimonic 115 passed the criteria specified but there were other areas to be addressed while making final selection. That included processing and manufacturability of turbine as per requirements specified. As far as processing is concerned, Nimonic 115 requires precipitation hardening (heat treatment) to achieve desired mechanical properties. But the hardened alloy could not be machined using normal machining setups, so study work was done and it was found out that numerically controlled Electro Chemical Machining (ECM) / Electro Discharge Machining (EDM) can be used to machine any conducting material regardless of its hardness in desired shape with reasonable accuracy [14, 15].

12. CONCLUSION

In this work, a two stage material selection procedure is defined for the high performance turbine blade for gas turbine engine. The same is followed in this paper with provided set of conditions for the selection of appropriate material. In this the provided selection list is narrowed down based on FE results obtained using Multiphysis linear and non-linear FE analysis. Finally, appropriate material is chosen with understanding of manufacturability.

Overall, this paper presents a step by step process using Multiphysics analyses for the selection of high performance material for the turbine blade which can generalized to many other appropriate applications.

REFERENCES

1. Immarigeon, J.-P. :The Super Alloys: Materials for Gas Turbine Hot Section Components, *Canadian Aeronautics and Space Institute Journal* (1981), Vol. 27, pp 336-354.
2. Singh, M. and G. Lucas, *Blade Design and Analysis for Steam Turbines* 2011: McGraw-hill.
3. Boyce, M.P., *Gas Turbine Engineering Handbook 2006*: Elsevier Science.
4. Glenny, J. E. Northwood, and A. Burwood-Smith: Materials for Gas Turbine, *Int. Met. Rev:* 20, (1975), pp 1-28.
5. *Special Metals Corporation: Material Handbook of High Performance Alloys* (2001). http://www.specialmetals.com
6. Meetham, G.W., H. Van de Voorde, and M.H. Voorde, *Materials for High Temperature Engineering Applications 2000*: Springer.
7. ANSYS® Multiphysics, Version 12.0
8. ANSYS® Inc., Theory Reference, 1Structures, 2Structures with geometric non-linearities, 3Structure with material non-linearities.
9. ANSYS® Release 9.0, Documentation, Structural Analysis Guide.
10. Pro-E, PTC Ltd., US
11. Nagel, Roger N.; Braithwaite, Walt W.; Kennicott, Philip R. (1980), Initial Graphics Exchange Specification IGES, Version 1.0, Washington DC: National Bureau of Standards, NBSIR 80-1978
12. C.T.F. Ross: Finite Element Methods in Structural Mechanics: 1985, John Wiley and Sons, Inc.
13. Leckie, F.A. and D.J.D. Bello, Strength and Stiffness of Engineering Systems 2009: Springer London, Limited.

14. Bin, H., *Computer Aided Production Engineering: Cape 2001-2002*: John Wiley & Sons.
15. Steve F. Krar and J. Williams, *Oswald: Technology of Machine Tools*, 4th Edition 1991, McGraw-Hill Co.