Experimental Study of Analysis of Various Methods used for Reduction of Creep in Turbine Blades

Soham S. Mhatre
Department of Mechanical Engineering
Lokmanya Tilak College of Engineering, Koparkhairane, Navi Mumbai 400709, India

Rupesh H. Singh
Department of Mechanical Engineering
Lokmanya Tilak College of Engineering, Koparkhairane, Navi Mumbai 400709, India

Suprabhat A. Mohod
Asst. Professor Department of Mechanical Engineering
Lokmanya Tilak College of Engineering, Koparkhairane, Navi Mumbai 400709, India

Abstract - The process of producing mechanical work from combustion of gases has changed a lot since the advent of gas turbine engines. Utilizing the maximum energy of high pressure-temperature gases to obtain high power output from rotating turbine blades has been the primary objective. The advancements in construction, design, material science, analytical studies and operating conditions have collectively helped in increasing the working temperatures and power output along with efficiency and lowering the environmental impact. Turbines have carved a niche in supplying high power outputs in land based applications as well as aeronautics. It is the augmenting need of getting higher power outputs, extending component life & decreasing environmental impact which constantly motivates engineers & designers to come up with new ideas and a way to implement the same. After all the advancements in turbine technology, the one crucial factor that constantly needs to be tackled is creep. A modern day turbine is most likely to fail due to creep in the turbine blades. Natural causes for which, being prolonged thermal stresses and fluctuating loads. This instantly makes us think of cooling measures. Though cooling is crucial, it is not the only way out. The stresses induced during the working conditions demand alterations in material composition, design, angle of blades and protective coatings too. The following paper incorporates the review of some significant research done to overcome the hurdles in reducing creep and extending the turbine blade life using different techniques and approach.

Keywords: Air cooling, bond coat, thermal barrier coating, water air ratio, Design & optimization, super alloys.

I. INTRODUCTION

Turbines can be delineated as a mechanical device which works by the action of fluid flow and converts the rotary motion into useful work. They are heavily used in energy production sectors to produce energy on a larger scale which can be used further by industries to run heavy and agile machineries. They tend to work at higher speed producing higher power density. Turbine consists of a rotor assembly which consists of a drum or shaft and several blades attached to it. The moving fluid imparts motion to the blade which in turn provides the energy to the shaft or the rotor. The vital component that is used for the manufacturing of turbines is the blade. The designs of the turbine blades are evaluated several times for the efficacious performance of turbines and also the blades endure for a longer period of time.

A turbine blade though humble, is one of the most purposeful and crucial of all components of the entire system. It is responsible for fulfilling the sole intent of turbines which is converting the energy obtained from high pressure and temperature gases from combustion into useful work. While performing this task, it undergoes tremendous amount of stresses due to high temperature gases hitting the blade surface, centrifugal force, fluctuating load conditions, and prolonged exposure to heat. The need for producing strong, long lasting blades for higher power outputs and increasing efficiency of the system, various measures have been thought of, tried, tested and worked upon over the years. The twisted profile/angle of blade from hub to tip is also an important parameter as it influences the inlet and exit velocities of fluid with low drag. Lowering drag helps in achieving the desired output but with an ease. Advanced blade profiles cut in smoothly and suck a large mass of air which passes through without hindering the turbine rotation. Switching to new metals and alloys have enabled high working temperatures up to 1600^{o}C which was initially only limited to around 800-900^{o}C. Ceramic composites are now taking over due to their noteworthy performance at high temperatures. Power output is mainly related to the turbine inlet temperature (TIT) which means increased power output can be achieved by increasing the inlet temperature of gas. This however induces stress in turbine blades leading to creep which is a crucial cause of blade failure. Thus finding measures to control creep in blades is a primary concern. The solution for this breaks down to various factors. Every factor even minutely related to creep must be studied and taken into consideration while designing any model. These factors range from microscopic to macroscopic levels. Right from choosing different materials to the process used for manufacturing, using advanced protective layers, the intermediate layers used to assist coating layers, no. of coating layers and their composition, effect of environmental factors, alteration in working conditions and similarly every little parameter should be studied for their influence on blade performance and how their alteration will affect the overall outcome of turbines. Such analysis leads to ingenious solutions.

II. CREEP - A PRIME HURDLE

This hindrance can be simply explained as a slow killer of engineering materials exposed to high thermal and mechanical stresses over a prolonged period. It is result of sliding of grain boundaries relative to adjacent layers. Creep begins in the form of voids developed in the stress prone area. Further stresses add to the size of voids, eventually leading to crack formation and then failure. The entire creep mechanism consists of 3 stages. It is only in the 3rd stage of the mechanism that the defects in the material are visible. Hence early detection of failure is difficult. It is unfortunately a tendency of any material under stress and hence cannot be discarded completely. However, the rate of creep can be brought down to a minimum resulting in increased material life. Thus we reduce creep we reduce failure, which eventually adds to increased working temperatures for higher work output. It is a function of time, stress and material property. Designers, engineers and researchers continue finding new ways to tackle cooling. Analysis of failure from macroscopic to microscopic level has become an essential part of research. With developing technology and simulation software, experimental models can be made and tested. Virtual simulation and effect of the various factors on a model can be analyzed and alterations can be made accordingly at an early stage thus reducing cost of research/production. As the research is advancing, its complexity is increasing. Every minute parameter and calculation is being considered so that no possibility is overlooked. Details regarding the working conditions and external environmental factors are also being taken into account

III. ADVANCEMENT OVER THE YEARS

The key to increased blade life lies in reducing the impact of the increased temperature on blades. This particular hurdle has no single solution and needs to be looked at from different angles of design, material science as well as surface engineering. Efforts have been put in since the inception of turbines to overcome this hurdle and reach higher limits of performance.

A. ALLOYING

Moving from heavy cast steel to nickel based super alloys for manufacturing which incorporate chromium, cobalt, and rhenium have helped in reducing weight while increasing the strength of blade material. Alloying helped in modifying the properties and microstructure of material while increasing or retaining its strength. This contributed in increasing the power to weight ratio of the turbine. Ceramic and its composites are also entering the field due to its stability at high temperatures and hardness. The objective of alloying has been to obtain a material that is light yet strong, durable, stable at rigorous working conditions and cost efficient.

B. MANUFACTURING TECHNIQUES

New processing techniques like vacuum induction melting and hot isostatic pressing (HIP) have contributed in producing precise composition alloys, decreasing porosity and increasing density of ceramics leading to enhanced mechanical properties of material. VIM simply put is a process of melting metals in vacuum with the heat generated via electromagnetic induction. This gives more control over the temperature and precise gradual blending while making alloys. HIP as the name suggests is a pressing operation performed at elevated temperature in the presence of inert gas to avoid reaction. As the temperature rises, the pressure is increased and applied to the material uniformly in all directions, resulting in decreased shrinkage, cracks, irregular depositions and voids. Further directional solidification technique helped in getting rid of the voids and cavities formed in the material during casting thus strengthening it and making less susceptible to failures due to internal defects. Investment casting contributed in producing alloys of high accuracy and reliability.

C. THERMAL BARRIER COATINGS

The above mentioned measures sure made the blade material strong however the direct impact of heat and friction made the blades vulnerable to damage. This led to the formulation of thermal barrier coatings (TBC). They are basically protective layers which insulate the underlying metal/alloy from external heat, corrosive agents. They facilitate working temperatures higher than the melting point of underlying material thus increasing the immunity of blades. Starting with aluminide coating, they too underwent advancement leading to improved ceramic coatings providing better protection. However minute cracks or leakage in TBC meant accelerated corrosive and degrading action on the substrate. This questioned the reliability of TBC, which then brought up the significance of bond coats. Bond coat is an intermediate layer of polymer that prevents oxidation or corrosive action and also strengthens the bond between surfaces in contact leading to increased adhesion of the TBC and alloy substrate. Combined with the super alloy substrate, TBC upped the TIT by up to 90º -100ºC. All these efforts collectively have increased the blade life and taking the operating temperature limit from 850º C to more than 1500º C.

D. AIR COOLING

Apart from improving the quality of blades, the need for reaching higher limits of performance demanded additional external cooling measures. Initial cooling involved only providing coolant air to the blades. This however can hinder the flow of gases in the turbine region. Study of heat transfer and fluid dynamics collectively suggested film cooling and convection cooling as an appropriate cooling technique. This practice was further modified by changes in the blade design and structure, providing holes over the blade span for increasing coolant flow over blades. Steam then was thought of as an alternative to air as coolant and the results proved it to be a good option as well. As advancement continued, closed loop cooling using steam was introduced. This method fulfilled the purpose of cooling blades while also assisting in generating power.

Research continues in this field to get the best out of turbines. Not every research attains success but its result helps in understanding the drawbacks of a particular alternative and assists in further analysis. The following paper reviews some of such significant research done in the direction of reducing creep in turbine blades.

IV. REVIEW OF SOME RESEARCHERS

1. *Sanjay et al [1]*

The following paper studies the different blade cooling techniques with respect to design of the blade. 7 cooling methods have been considered and the result of each when employed to the blades has been compared. The paper also takes into account the effects of cooling on the overall performance of the turbine cycle.

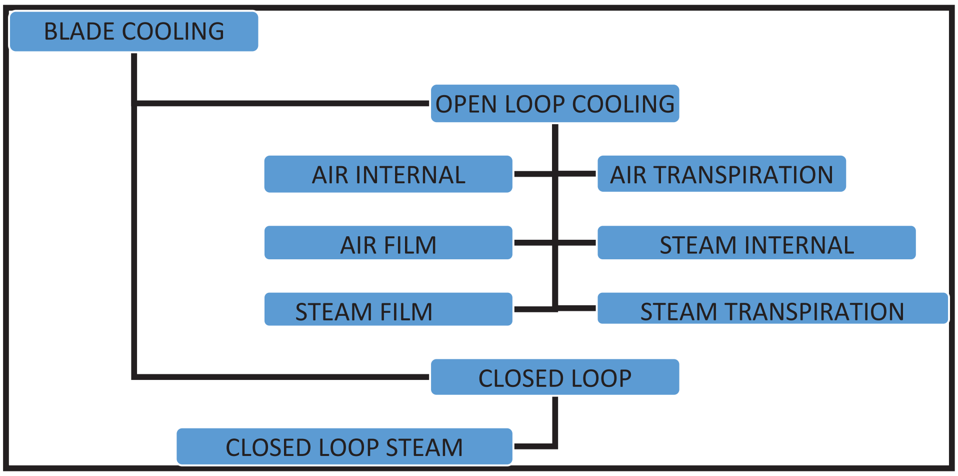

Figure 1. Classification of blade cooling methods

1.1 *Open loop cooling*: The cooling air is obtained from appropriate compressor stage and fed to the blade surface, after which it combines with the exhaust gases of turbine. Steam needed for cooling is obtained from the exhaust of high pressure steam turbine and once it has cooled the blades, the hot steam mixes with the exhaust gases similar to air.

- Air internal convection cooling (AICC): As the name suggests, cooling is by means of convection. Internal holes and passages are drilled in the core of the blade and air is passed through them from base to tip.
- Air film cooling (AFC): Another application of convection cooling. However, the construction differs in terms of air passages, there are holes drilled at the leading edge of the blade which are connected to the internal passages. The air flowing through the core also comes out through the leading edge holes forming a uniform layer over the entire span of blade. This facilitates internal convection as well as external film cooling.
- Air transpiration cooling (ATC): A further modification of air film cooling. Here the complete span of blade has holes drilled in various patterns to increase the cooling rate.
- Steam internal convection cooling (SICC): Similar in construction to internal air convection cooling but with steam as cooling agent.
- Steam film cooling (SFC): Similar in construction to air film cooling but with steam as cooling agent.
- Steam transpiration cooling (STC): Similar to air transpiration cooling but with steam as cooling agent.

1.2 *Closed loop cooling:* The only difference in closed loop cooling is that the steam after cooling is mixed with the steam coming out of the heat recovery steam generator and fed back into the system.

- Closed loop steam cooling (CLSC)

Appropriate models of each alternative and calculations for the same revealed the following results:

- Graphical representation of (coolant flow rate) / (gas flow rate) VS (turbine inlet temperature) reveals that the coolant requirement increases with increasing turbine inlet temperature.
- AICC has the maximum coolant requirement followed by AFC, ATC, SICC, SFC, and STC in a decreasing order.
- CLSC has the least coolant requirement with increasing turbine inlet temperature.

- All methods give appreciable cooling up to a critical temperature, beyond which the increasing air flow hinders the turbine output due to excess air entering exhaust gases. However, that is not the case in steam cooling and it continues serving its purpose without interfering with the efficiency or power output.
- CLSC proves to be the most efficient cooling method as it functions over the complete range of turbine inlet temperature while also assisting the compressor for better power output.

1.3 Conclusion

- Steam cooling has emerged out as a leading alternative for cooling turbine blades due to its high heat carrying capacity. Closed loop convection cooling though the best option adds to the complexity of the system.
- Transpiration cooling is a good alternative and along with steam as coolant transpiration cooling can turn out to be a good combination.
- The pressure with which coolant comes out of the pores should be give due consideration. It should be just sufficient to form a film over the blade span and not eject out like a jet interfering with the oncoming gases.
- The amount of coolant provided should not exceed the limiting value and lose the sole purpose of increasing turbine performance. We wouldn't want a turbine with long lasting blades but compromising on turbine output.

2. *S.Eshati et al [2]*

This research paper focuses on the influence of water air ratio (WAR) on the heat transfer rate of coolant and creep life of high pressure gas turbine blades. Results at various WAR values are studied and compared. The study also takes into consideration the effect of thermal barrier coating, operating conditions and design parameters of the blade. WAR or humidity has often been overlooked in a turbine, however it plays a significant role in humid conditions.

		Density (kg/m^3)	**Thermal conductivity (W/m-K)**	**Thickness (m)**
1.	**Nimonic-90**	8180	25.8	0.002
2.	**TBC-EBPVD**	-	1.5-2	0.000125

Table 1. Specifications of substrate alloy and TBC

The researchers have started off with an overview of all the air cooling methods that have been worked upon or are currently in practice including thermal barrier coatings. However, these factors have been studied considering dry air or steam coolant only, say the writers. The study undertaken in this paper considers changes in fluid properties through variation of Cp, γ, R, Reynolds no, Nusselt no, density and other parameters. The study makes use of analytical software TURBOMATCH which is capable of simulating and analyzing different thermodynamic processes as well as engine performance (turbines, compressors, nozzles). The substrate and TBC used for the analysis is a first stage turbine blade of a high pressure gas turbine whose details are mention in the table.

2.1 *Observation*

Values from experimental data were entered as a reference. Further, the values were modified and checked for different WAR values. Its effect on different sections of the blade span was compared and the following observations were made:

- Increased WAR decreased the air coolant temperature however for a constant WAR value coolant temperature increased from blade hub to tip thus reducing the difference between the blade temperatures at the 2 sections. The changes in parameter values due to increasing WAR are listed below, where t is the thickness of substrate and T is the coolant inlet temperature.

Parameter	t	ρ	μ	Re	Nu	T
Hub to tip	▲	▲	▲	▼	▼	▲

Table 2. Change in coolant properties due to increasing WAR

- Change in WAR decreased blade temperature at each section however the change was significant from blade mean to tip.
- Increasing heat transfer coefficient due to increased WAR reduced creep significantly.
- Increased WAR increased Nusselt no which is responsible for the heat transfer on coolant side.

2.3 *Conclusion*

- Water air ratio has a significant influence on the functioning of coolant as seen from the analysis and further research should be carried out to test the real time consequences of the same.
- Increasing the water content in coolant should be accompanied with reliable TBC for blades to prevent its impact on the blade material.

3. *H.M.tawancy et al [3]*

This paper emphasizes on the influence of bond coat-substrate combination based on the failure mechanism and application of thermal barrier coatings. It also takes into consideration the methods used for applying the bond coats and the number of coating layers.

3.1 *Experimental setup and materials used*

There are rods of 10 cm length, 8mm diameter & discs having 25mm diameter, 8mm thickness used in the process. 3 varieties of substrates, the details of which are mentioned in the table below are used. Here the CMSX-4 and CMSX-10 are single crystal alloys while MAR M002DS is a directionally solidified polycrystalline alloy. Table below gives the chemical composition of alloys by %wt.

	Element	MAR M002DS	CMSX-4	CMSX-10
1.	Ni	Balance	Balance	Balance
2.	Cr	9	6.5	2
3.	Ti	1.5	1	0.2
4.	W	10	6	5.3
5.	Mo	0.5	0.6	0.4
6.	Zr	0.55	-	-
7.	Co	10	9	3

8.	**Al**	**5.5**	**5.6**	**5.7**
9.	**Ta**	**2.5**	**6.5**	**8**
10.	**Re**	**-**	**3**	**6**
11.	**Hf**	**1.25**	**0.1**	**0.03**
12.	**C**	**0.15**	**-**	**-**

Table 3. Specifications of alloys used as substrates

The bond coats used in the experiment are listed along with their configuration:

	Bond coat type	Composition
1.	3 layer pt modified bond coat	Outer layer consists of PtAl2 dispersed in a matrix of β phase based upon NiAl composition followed by an intermediate layer of β phase & an inner inter diffusion zone.
2.	2 layer Pt-aluminide bond coat	It consists of an outer layer of Pt aluminide β phase followed by an inter diffusion zone.
3.	Low cost bond coat	It consists of an outer layer of Pt rich γ^I phase based upon Ni3Al composition containing small islands of γ phase (Ni rich solid solution) & an inner layer of coarse γ^I particles dispersed in a matrix of γ phase.

Table 4. Details of Bond coats used in the analysis

- The top coat or TBC used here is zirconia-7%wt yttrium for all specimens.
- Different techniques used for characterization of microstructures of the coating layers are scanning Electron microscopy SEM, x-ray-diffraction, EPMA, Energy dispersion x-ray spectroscopy EDS, Transmission electron microscopy TEM
- The specimens are treated with bond coats and TBC and tested for different combinations of bond coat-substrate. They are then tested using the above mentioned techniques. The observations made are listed below.

3.2 *Observations*

- Changing the substrate-bond coat combination resulted in considerable changes in oxidation rates and affected the bond coat life hugely.
- Bond coats having $\gamma+\gamma^I$ structures perform poorly on polycrystalline alloys but perform considerably well on single crystal alloys.
- Platinum aluminide bond coats processed by chemical vapor deposition based upon pt modified β phase perform better on polycrystalline alloys than bond coats processed by pack cementation process.
- Variation in behavior for different bond coat-super alloy combination is dependent on factors like oxidation rate of bond coat, inter diffusion between bond coat and substrate and phase transformations in the bond.

3.2 *Conclusion*

As observed from experimental analysis, bond coat and super alloy combination has major impact on the TBC performance as it relies on the bond coat. The coat application techniques too affect the microstructure of the layer leading to significant changes in result.

4. *L.wang et al [4]*

This paper highlights the design and optimization of coating structure of TBC fabricated by atmospheric plasma spraying (APS). It highlights the effect of coating structure on enhancing the thermal insulation effect and reducing residual stresses. The study makes use of finite element method using a simulation software ANSYS.

4.1 *Experimental setup and procedure*

The analysis takes into account 4 coating layers namely bond coat, inter-layer (50%wt.YSZ+50%wt. NiCrCoAlY), ceramic layer (YSZ) which is yttrium stabilized zirconium and an additional top layer of $La_2Ce_2O_7$ which are abbreviated as BL, IL, YSZ and LC respectively. The substrate used is a Ni-alloy with dimensions as 25mm diameter and 6mm thick. The parameter values used for simulation are as listed below:

	Material	**T (°C)**	**E (G-pa)**	**ρ (kg/m³)**	**υ**	**α**	**K**	**C**
1.	**YSZ**	**25 400 800**	**53 52 46**	**4400 4400 4400**	**0.25 0.25 0.25**	**7.2 9.4 16**	**1.5 1.5 1.2**	**500 576 637**
2.	**$La_2Ce_2O_7$**	**25 400 800**	**49 44 38**	**7100 7100 7100**	**0.24 0.24 0.24**	**6.7 8.9 13.7**	**1.12 0.93 0.90**	**494 565 607**
3.	**NiCoCrAlY (50%) + YSZ (50%)**	**25 400 800**	**156 146 89**	**5860 5860 5860**	**0.275 0.275 0.275**	**11 19 35**	**3.1 3.8 5.6**	**517 621 689**
4.	**NiCoCrAlY**	**25 400 800**	**225 186 147**	**7320 7320 7320**	**0.3 0.3 0.3**	**14 24 47**	**4.3 6.4 10.2**	**501 592 781**
5.	**Substrate of Ni-alloy**	**25 400 800**	**200 179 149**	**8220 8220 8220**	**0.3 0.3 0.3**	**14.4 14.4 14.4**	**11.5 17.5 23.8**	**431 542 627**

Table 5. Specifications of coating layers used in the analysis

4.2 *Result and Conclusion*

The specimen was tried and tested for different combinations of coating layers and varied thickness of the same. The results obtained highlighted some key points stated below:

- Residual stresses in protective coatings mainly occur due to the mismatch between thermal expansions coefficient of adjacent layers, hence the arrangement of layers should be appropriate.

- Adding protective layer coatings is not the apt solution to increase thermal insulation of the blade as it results in increased residual stress leading to early failure of protective layers. The BL and IL only serve as compensators in thermal expansion coefficients and should be in the range of 60-120μm.

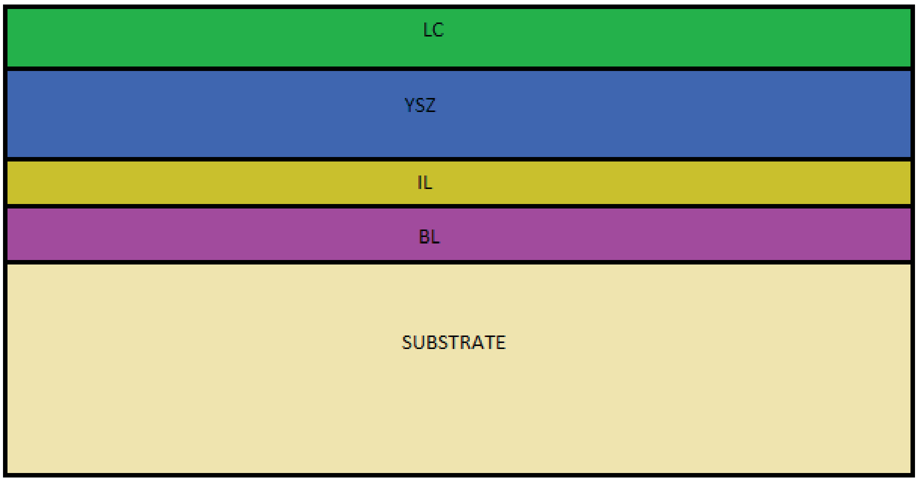

Figure 1. Representation of coating composition

- Comparison of temperature distribution & effective thermal conductivity for LC/YSZ/IL/BL and YSZ/IL/BL, YSZ/BL suggest LC/YSZ/IL/BL as the apt combination for TBC system. Further a double layer of ceramic coating to the LC/YSZ/IL/BL system proved to be more effective in handling thermal shocks and high temperature oxidation and suggests double layer coating as a good alternative for increasing TBC efficiency.

5. *Xin zhou et al [5]*

Another study of the effect of using a double layer bond coat under the TBC top layer, particularly for a Ni based super alloy has been undertaken here. The substrate taken is Ni3-aluminium based super alloy (30x20x1.5) mm. The double layer bond coats used are (Ni, Pt) Al and NiCrAlYSi respectively.

The (Ni)Al layer was applied by electroplating the base alloy with approximately 2μm of platinum followed with a vacuum treatment at 1030ºC, this was followed by aluminization at 1050ºC for 3h by industrial CVD process. The NiCrAlYSi layer was then deposited by ion-plating PVD. The final top coat of YSZ was applied by EB-PVD. The coatings were studied for their microstructures by x-ray diffraction and SEM techniques. The specimens were exposed to elevated temperatures and increasing cycles. The microstructures were checked for weight changes as well as defects at appropriate stages of testing. Some crucial observations were made in the process.

5.1 *Observations*

- The layers of coatings had good adherence with each other as well as with the substrate and TBC at their interfaces. Double layer bond coats have better adherence than single ones in the long run.
- Double layer bond coat provides more supply of Al for diffusion thus extending the life of TBC. A double layer bond coat also extends the thermal cycles of the blade and helps in reducing the substrate surface temperature by 100-200ºC.

5.2 *Conclusion*

The double layer bond coat sure has advantages over the single layer, with increased reliability and insulation properties. Any drawbacks faced in the technique can be overcome by modification/advancement in the coat deposition techniques.

6. LI Xu et al [6]

This paper focuses on the advanced air cooled turbine blades by Rolls Royce. The blade tip design of the blades to prevent leakage, which makes it unique and how modern simulation software can be used to get the best results is explained.

The Turbine inlet temperature of turbines have been increasing over the years dude to numerous changes in the design, material composition and manufacturing techniques. Complicatedly shaped holed on blade surface have enabled convection cooling. The use of CMSX-4 casting and thermal barrier coatings have contributed greatly to increased working temperatures. Rolls Royce makes use of HP and LP coolant for cooling blades, while HP coolant flows from the holes at leading age forming a film, the LP coolant flows through the core of blade giving better cooling configuration. Over tip loss was seen a hurdle to be tackled by using shrouded blade tip which decreased the clearance between blade tip and stationary boundary. This however increased the centrifugal stress on blades. An alternative to this was found in introducing a groove or depression at the blade tip.

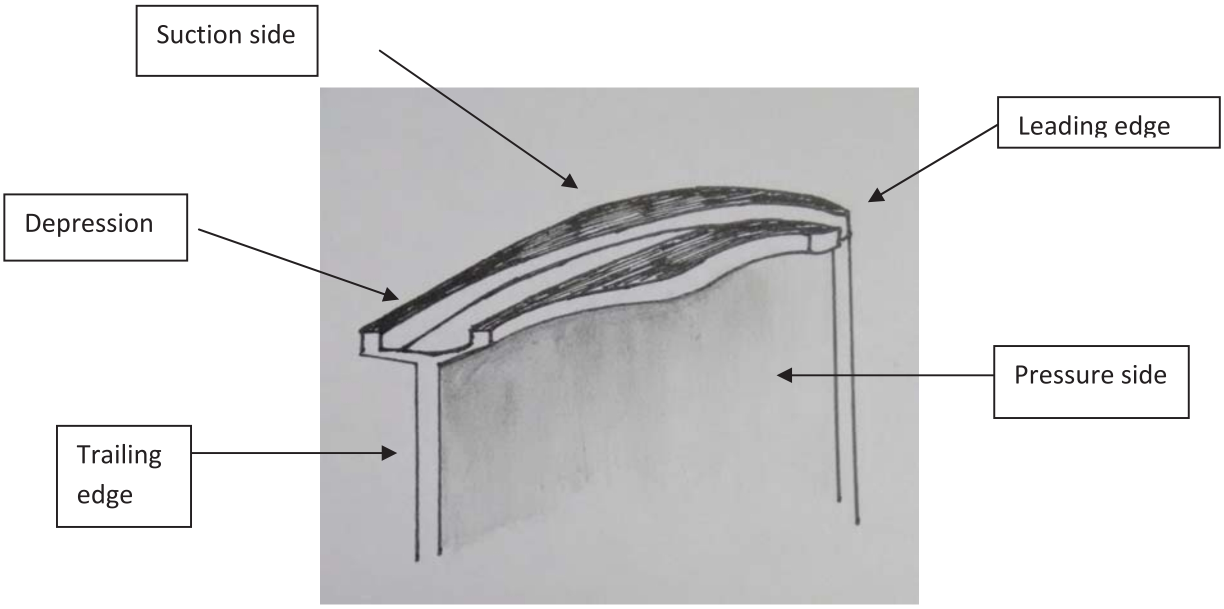

Figure 2. Winglet tip design to prevent over tip losses

This depression captures the leaking air and pushes it into the main flow. It is named as winglet tip design and work continues to be done for making it effective. Rolls Royce also stresses on the modification of material and manufacturing technology. Moving on to super alloys, investment casting, directional solidification, dual wall cooling, adapting new techniques and ideologies make Rolls Royce a leading producer of turbines. It stresses on the application of analysis software to understand the barriers and tackle them effectively using various methods.

V. CONCLUSION

On studying the papers mentioned above, it can be seen that there has been a tremendous progress in bringing down the failures occurring in turbine blades. The study has gone from design parameters to microscopic level analyzing each and every hurdle coming in the way and tackling the same with the knowledge we seek from past mistakes, experimental failures, natural phenomenon and all this combined with the new age technology which helps researchers get to the root cause of any problem. ‘Creep’, a nightmare for any structural engineering application, as the name suggests finds its way out somehow. This defect needs to be looked at from different point of views. The complexity of its behavior is what demands exceptional solutions. The above mentioned research studies portray the benefits of each alternative, maybe a combination of certain alternatives can help curb down the creep failure further. Also blade cooling measures that also enhance the system’s output would be highly appreciated like the closed loop steam cooling approach, a humble yet powerful solution.

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