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Effect of fouling, thermal barrier coating degradation and film cooling holes blockage on gas turbine engine creep life

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Abstract

Gas turbines are sometimes operated in very hostile conditions due to service exigencies. These environments are characterized by degradation modes such as fouling, thermal barrier coating degradation and blockage of cooling holes which affect the creep life of engines. Therefore this paper presents a performance-based creep life estimation model capable of predicting the impact of different forms of degradation on the creep life of gas turbines. The model comprises performance, thermal, stress, and life estimation models. High pressure turbine blade was selected as the life limiting component of the gas turbine; therefore the integrated model was employed to investigate the effect of engine degradation on the creep life of a high pressure turbine blade of an aero derivative model gas turbine engine using a Creep Factor approach. The results shows that engine degradation affect the performance of gas turbine component which in turn affect their creep life.

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Keywords: Fouling; Degradation; Creep life; Thermal barrier coating; Creep factor

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1. Introduction

Gas turbines are sometimes operated in chemically aggressive and harsh operating conditions such as the desert, marine, coastal and offshore environments due to service exigencies, where the working fluid (atmospheric air) is often contaminated and harsh. Under these harsh conditions, gas turbine components such as compressors, combustors and turbines which are usually designed for total life, experience different forms of degradation due to the ingestion of contaminants that often lead to their premature failure. Some of these degradations that gas turbine components suffer in such operating environments include fouling, thermal barrier coating (TBC) degradation, plugging of cooling holes etc. In a bid to minimize engine component degradation due to ingestion of these harmful contaminants, air filtration systems are used to control the quality of air entering the gas turbine intake [1]. However, complete filtration of the intake air is not feasible, because of the tiny nature of some these contaminants and the associated pressure drop, cleaning requirements, filter replacement and the overall increase in engine weight (aero gas turbines) [2].

However, most creep life prediction models for life critical components are built based on only operating temperatures, stresses and Engine Operating Time (EOT) without considering the effect of some of these degradation modes. Sometimes, substantial safety factors are included to ensure a failure free operation because, their predictions are not environment specific, but based on empirical experience. According to Naeem et al [3], such approaches may not be accurate as they do not represent the actual operating environment of the components within gas turbines. Moreover, the methodologies and criteria used to arrive at such life predictions and recommendations are obscure. The implication is that either the creep life of the component will be overestimated or underestimated. Therefore, to enhance the prediction of creep life of gas turbine engine components in such hostile and chemically aggressive environments, degradation modes such as fouling, TBC degradation etc which contribute substantially to the failure mechanisms of engine components could be taken into account. Therefore, this paper aims at introducing a performance-based integrated creep life estimation method being capable of predicting the

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impact of different degradation modes on the creep life of gas turbine engines. Such a model provides end users of gas turbines with a flexible creep life estimation method which is capable of performing feasibility studies on the effects of environmental factors on the creep life of gas turbines. The work has been focused on the impact of hot corrosion, oxidation, fouling, TBC degradation and plugging of cooling holes on the creep life of high pressure turbine (HPT) blades. However, the effect of oxidation has been published elsewhere [4], hence this paper focuses on only the impact of plugging of cooling holes, TBC degradation and compressor fouling on HPT blade creep life.

Nomenclature

TBC	thermal barrier coating
EOT	engine operating time
HPT	high pressure turbine
CMAS	calcium-magnesium-alumina-silicate
NGV	nozzle guide vane
LE	leading edge
TE	trailing edge
RTDF	radial temperature distribution factor
LMP	Larson-Miller parameter
CF	creep factor
FI	fouling index
TET	turbine entry temperature
PCN	shaft speed

2. Methodology

A HPT blade of a two-shaft aero derivative model gas turbine engine is selected as the creep life limiting component of the gas turbine. This is due to the fact that it experiences the highest mechanical and thermal loads. Consequently, the idea of this research is to analyze the effect of compressor fouling, TBC degradation and plugging of film cooling holes on the creep behavior of the HPT blade using a Creep Factor approach [5]. In doing this, an engine performance model was created using TURBOMATCH [6], which is a gas turbine engine performance simulation code developed at Cranfield University. A creep life model was set up and the data from the performance model and information available in open literature was used for the prediction of engine creep life. Degradation indexes ranging from 1% to 25% were used to quantify the impact of different degradation modes on the performance and creep-life of the model engine. The integrated model was subsequently used to assess the impact of fouling, TBC degradation and plugging of film cooling holes on the creep life of the model gas turbine engine.

3. Environmental factors

The ingestion of air contaminants such as CMAS-type materials, sand/dust, salt, etc. into gas turbines could cause fouling/erosion problem for the compressor section and TBC degradation as well as plugging of cooling holes for the turbine section. According to Santini et al [7], the ingestion of air contaminants can generate plugging of cooling holes and fusion of particles in the hot sections of gas turbines. Similarly, particles like sea salt or volcanic ash that endure through the compressor are carried into the airstream of the burner where they melt due to the high temperature and deposit on the turbine blades in a molten state thereby plugging the cooling holes and attacking the TBC. In this section, brief description of fouling, blockage of cooling holes and TBC degradation is presented.

3.1. Fouling

Fouling is caused by the adherence of particles less than 10μm (such as salt, dust, ash, smoke, carbon, mist etc.) to airfoils and annulus surfaces [8]. Fouling often leads to changes in airfoil shape, surface roughness, or changes in airfoil inlet-angles. It has been widely reported that gas turbines operating in industrial, marine, rural and agricultural environments will experience compressor fouling [9; 10]. Commercial filters can remove these particles to a reasonable extent; however, most submicron particles are difficult to remove due to their tiny nature. Compressor fouling reduces the compressor mass flow rate, pressure ratio and the cycle efficiency which subsequently leads to a reduction in power and increase heat rate [11; 12]. In a bid to recover lost power, firing temperatures are raised which has a detrimental effect on the blade creep life.

3.2. Blockage of cooling holes

The complex design of HPT blade cooling geometry presents itself with a serious issue especially when operated in salty, dusty or sandy environments because the cooling holes easily becomes blocked by tiny particles. Blockage of these holes means the turbine blade cooling system will not function at it optimum efficiency. The blockage of film holes reduces the film cooling efficiency and this causes an increase in blade metal temperature which will reduce the blade creep life.

3.3. Thermal barrier coating degradation

Air contaminants such as sand/dust, volcanic ash and salt are sometimes efficiently milled into fine particles during compression and subsequently carried beyond the compression section into burner section. Subsequently, when the air is heated up during combustion, these debris melt and are propelled into the nozzle guide vanes (NGVs) and turbines where they are deposited on the blade surface. The resultant effect is that the molten deposit will chemically attack the coatings on the blade surface. The attack will result in a gradual loss of TBC thickness. When this happens, the overall cooling effectiveness reduces which leads to a rise in blade metal temperature. The rise in blade metal temperature will cause a subsequent reduction in blade creep life.

4. Blade creep life assessment

To predict and analyze the impact of degradation modes such as compressor fouling, TBC degradation and plugging of cooling holes on the creep life of gas turbine engines, it was imperative to develop a creep life assessment model. Therefore, a physics-based creep life assessment model was developed based on the earlier work done at Canfield University [5; 13] and applied to the HPT first stage rotor blade. The creep life assessment model was based on an analytical approach consisting of three main sub models which include stress, thermal and life estimation models. Fig 1 shows the methodology used for the research.

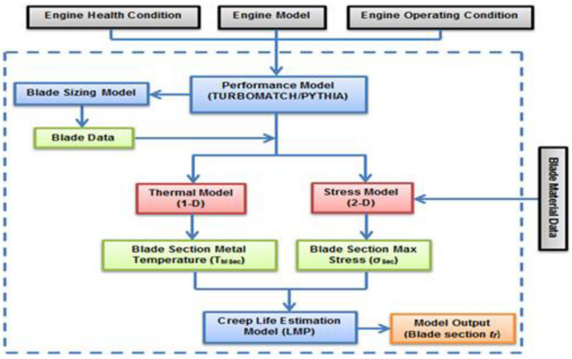

Fig 1. Integrated creep life assessment model.

4.1. Stress model

The stress model calculates the stress distribution along the blade and it was developed based on the algorithm provided in [4]. The 2 main sources of stress considered are stresses due to centrifugal load caused by engine rotation and gas bending momentum. The variations of the blade stresses are predicted at locations along the blade span and chord. At span-wise, the blade span was divided into sections at intervals of 25% of the blade span whereas the chord was split into three areas namely blade leading edge (LE), trailing edge (TE) and the back of the blade.

4.2. Thermal model

The thermal model estimates the blade metal temperature distribution. It was developed and used to estimate the blade metal temperature. The blade is regarded as a heat exchanger which is subjected to a mainstream of hot gas flow from the burner. The main considerations of the model are the cooling methods, the blade geometry, the TBC thickness, the heat transfer coefficients, the gas properties, the radial temperature distribution factor (RTDF), the blade material etc. More details of the thermal model used in this paper can be found in [4].

4.3. Life estimation model

The creep life estimation model evaluates the creep life of blades based on the estimated stress and metal temperature and displays the results as a Creep Factor. The Larson Miller Parameter (LMP) [14] is used to evaluate the creep life of the HPT rotor blades and it is expressed in Equation (1).

$$t_f = 10^{\left(\frac{1000P}{T_M}\right) - C} \tag{1}$$

Where t_f is time-to-fracture; T_M is the material temperature; P is the *LMP* while C is the parameter constant.

4.4. Creep factor

Creep Factor (CF), a concept developed by Abdul Ghafir et al. [9] is adopted in this study to estimate the impact of actual operating conditions on creep life consumption of gas turbine engines. It is defined as the ratio between the actual creep life and the creep life at a reference condition. The CF approach appraises the rate of creep consumption relative to a specific operating condition desired by the operator. The concept of CF is further explained in [5].

5. Engine performance simulation and blade geometry

In order to study the impact of degradation modes on gas turbine engine creep life, a model aero derivative gas turbine engine similar to GE LM2500+ was created in this study using the engine performance specification provided by [15]. TURBOMATCH [6] was used to create an engine performance model shown in Fig 2 based on the engine configuration provided in [15].

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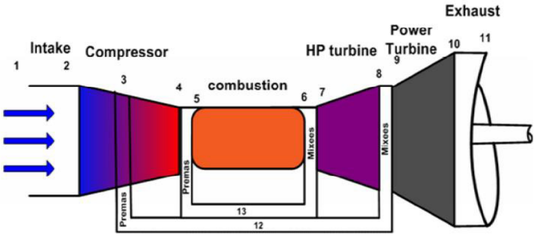

Fig 2: Layout of 2-shaft aero-derivative engine.

The model engine has an axial compressor driven by a compressor turbine, a combustor and a power turbine providing power output. Using the results from the engine performance simulations and available information from open literature, the blades of the first stage of the HPT of the model engine was sized using the constant mean diameter method [16]. The model HPT blade used for this study is described elsewhere [4].

6. Results and discussion

6.1. Effect of compressor fouling on blade creep life

The integrated creep life model was used to assess the impact of compressor fouling on HPT blade creep life. In doing this, different Fouling Indexes (FI) ranging from 1% to 4% are used to examine the impact of compressor fouling on the performance and creep life of gas turbines. The definition of FI is shown in Table 1 and the values are chosen based on typical values used to represent compressor fouling [16; 17]. Based on the defined FI in Table 1, TURBOMATCH was used to simulate the impact of compressor fouling on the model engine performance and the results are illustrated in Fig 3 and Fig 4.

Table 1: Classification of fouling index.

Fouling Index (%)	Change in mass flow capacity (%)	Change in isentropic efficiency (%)
1	-0.5	-1
2	-1	-2
3	-1.5	-3
4	-2	-4

The results show that compressor fouling increases the Turbine Entry Temperature (TET) and fuel flow (Fig 3). On the other hand, it reduces the mass flow and efficiency (Fig 4).

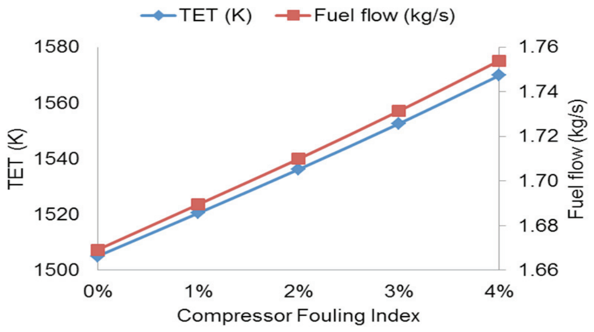

Fig 3. Effect of compressor fouling on TET and fuel flow.

The TET and fuel flow are increasing because compressor fouling causes reduction in blade efficiency due to tip clearances, tip chord variation and increased surface roughness. These effects subsequently results in less air passing through the compressor and thereby reducing the pressure ratio at a given non-dimensional speed line. Because of the reduced flow capacity and efficiency, to produce a given power output at constant PCN, the engine runs at a higher TET giving rise to high fuel flows (Fig 3) at reduced efficiencies (Fig 4). The rise in TET will in turn increase the blade metal temperature and consequently reduce the creep life of the turbine blades.

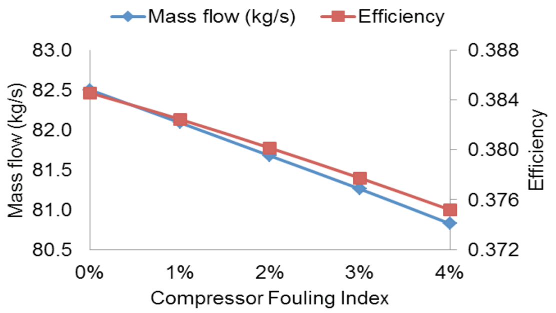

Fig 4. Effect of compressor fouling on mass flow and efficiency.

Consequently, the impact of compressor fouling on the blade metal temperature and creep life was investigated and the results are shown in Fig 5 and Fig 6 respectively.

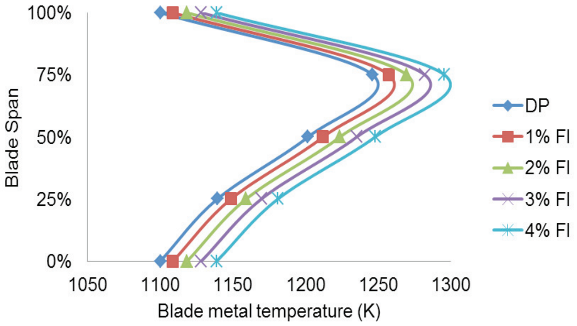

Fig 5. Effect of compressor fouling on blade metal temperature.

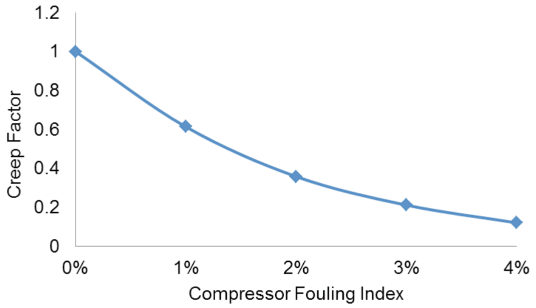

Fig 6. Effect of compressor fouling on HPT blade creep life.

In comparison with the baseline condition (DP), compressor fouling increased the blade metal temperature. The results were consistent for all the different points on the blade span and the severity increased as the FI was increased. From Fig 6, it could be seen that the CF reduced when the FI was increased. For instance, at FI of 1%, the Creep Factor has reduced from 1.0 to 0.61 but as FI is increased to 3%, the Creep Factor further reduced to 0.21. This means that in comparison with the reference condition denoted by 0% in Fig 6, at FI of 1% and 3%, the blades' creep life has reduced by 39% and 79% respectively. The values show that as compressor fouling increases, the creep consumption also increases.

6.2. Effect of film cooling holes blockage on blade creep life

The blockage of film cooling holes reduces the film cooling efficiency and this causes an increase in blade metal temperature which will reduce the blade creep life. The influence of film cooling efficiency loss on the blade metal temperature is shown in Fig 7.

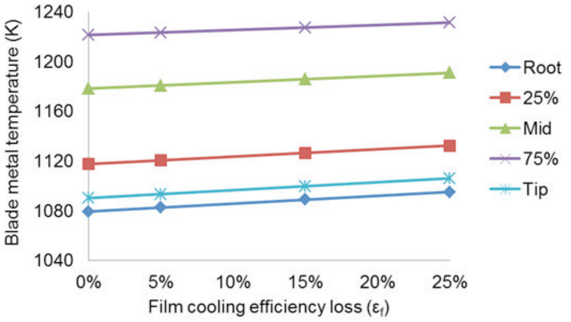

Fig 7. Variation in blade metal temperature due to loss in film cooling efficiency.

The results represents a situation where the HPT blades are suffering from either turbine glazing, CMAS attack or film cooling hole blockage, therefore the TBC and the convective efficiency are not affected hence not reflected in this analysis. The results show that for every percentage drop in film cooling effectiveness, there is a corresponding rise in blade metal temperature. Even though the increment is marginal, the overall impact on the creep life was massive.

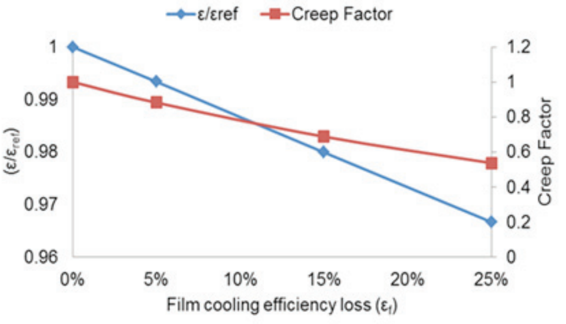

Fig 8. Effect of film cooling efficiency loss on HPT blade creep life.

Subsequently, the impact of film cooling efficiency loss on the rotor blade overall cooling efficiency, ε and creep life was investigated using the integrated life estimation model. The results illustrated in Fig 8 show that as the film cooling efficiency reduces, the overall cooling efficiency dropped. The reduction in ε increased the blade metal temperature (Fig 7) which in turn reduced the blade creep life. For instance, at 15% loss of film cooling efficiency from its original value, the overall cooling effectiveness, ε dropped by 2% while the creep factor reduced from 1.0 to 0.69 representing approximately 31% reduction in blade creep life. This means blockage of film cooling holes could have a significant negative effect on the blade creep life.

6.3. Effect of thermal barrier coating degradation on blade creep life

Similar to the previous cases discussed, TBC degradation affects the HPT blade metal temperature, overall cooling effectiveness, ε and creep life. The variation in blade metal temperature due to TBC degradation is illustrated in Fig 9. The result shows that for a given set of gas conditions with a pre-determined level of film cooling and convective efficiencies, TBC degradation will cause a rise in blade metal temperature. For instance, it could be seen in Fig 9 that at 15% loss of TBC thickness, the blade metal temperature at the blade mid-height increased from 1178K to 1187K representing about 1% increase in metal temperature. Subsequently, the impact of TBC deterioration on the overall cooling effectiveness and HPT blade creep life as calculated by the integrated life estimation model are shown in Fig 10.

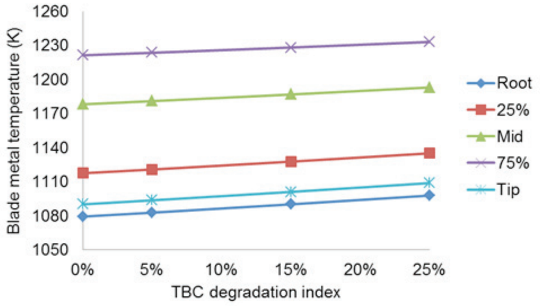

Fig 9. Variation in blade metal temperature due to TBC degradation.

The result in Fig 10 shows that a reduction in TBC thickness through either a chemical attack or erosion will cause a reduction in the blade cooling effectiveness which will in turn increase the blade metal temperature hence leading to a reduction in blade creep life.

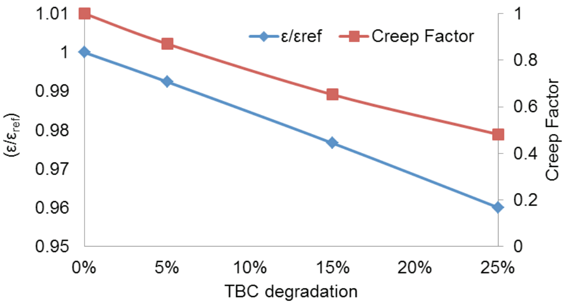

Fig 10. Impact of TBC degradation on the overall cooling efficiency and HPT blade creep life.

For instance as the TBC thickness reduced by 25% from its reference value, the overall cooling effectiveness dropped by approximately 4% while the Creep Factor reduced from 1.0 to 0.482. This means 25% loss of TBC thickness could halve the blade creep life. It is important to note that the internal convection cooling efficiency and film cooling effectiveness were kept constant. The results generally show the importance TBC in determining the creep life of gas turbine HPT blades.

7. Conclusion

This paper presents a novel creep life analysis model which has been used to assess the impact of fouling, TBC degradation and plugging of film cooling holes on the creep life of HPT blades. The results show that compressor fouling, TBC degradation and plugging of cooling holes have significant detrimental effect on the creep life of the turbine blades. For instance, at FI of 1% and 3%, the HPT blade creep life reduced by 39% and 79% respectively from its reference creep life. Similarly, 25% loss of TBC thickness from its reference value reduced the overall cooling effectiveness by approximately 4% which subsequently reduced the Creep Factor from unity (1.0) to 0.482. This means 25% loss of TBC could halve the blade creep life.

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