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FATIGUE ASSESMENT OF TURBINE BLADE BASED ON SURFACE COATING DEGRADATION AFTER EXTREME LOADING

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Abstract: *This study investigates fatigue damage in protective coatings and fatigue crack initiation in the substrate of the nickel-based superalloy ZhS6K, widely used in helicopter turboshaft engine turbine blades, within the framework of the damage tolerance principle. Despite its widespread use in service, the relationship between surface damage and subsurface fatigue crack development in ZhS6K has not been thoroughly investigated. The effect of coating degradation on the initiation and propagation of fatigue microcracks in the substrate material is analyzed and the damage tolerance methodology is implemented. A key contribution of this work is the identification of specific operational manoeuvres that produce high mechanical loads, leading to minor surface damage while causing major fatigue damage in the substrate. The proposed approach allows for an evaluation of blade damage that does not rely on complete load history data. This new approach can be generalized to other turbine blade materials and operating conditions.*

Keywords: Fatigue assessment, Turboshaft engines, Turbine blade, Surface coating

1. Introduction

Helicopters with a turboshaft power unit are sometimes exposed to extreme operating conditions, such as military training or rescue missions, which generate higher mechanical loads than originally designed and tested. These conditions may result in visually minor coating damage while causing major fatigue cracks within the substrate material. Such loading, coupled with barely visible degradation, can lead to non-standard defects with specific failure mechanisms. Failure of a turbocompressor rotor blade during flight can cause a power unit malfunction, leading to a highly probable catastrophic scenario.

Nickel-based superalloys are widely used in turbine blades of helicopter turboshaft power units due to their exceptional high temperature strength, creep resistance, and fatigue properties. Among these materials, the cast superalloy ZhS6K has been extensively applied in critical rotor blade components. Previous studies on nickel-based superalloys have primarily focused on creep–fatigue interaction or coating oxidation resistance (Swadźba et al., 1992; Chmiela et al., 2012), with limited attention given to the role of coating fatigue damage in the initiation of fatigue cracks within the substrate. For the ZhS6K material, the relationship between localized coating degradation and the formation of subsurface fatigue microcracks has

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not yet been comprehensively investigated. This knowledge gap limits the accuracy of current damage tolerance (DT) models for estimating the remaining service life of turbine blades in service. By establishing a link between surface coating condition and subsurface fatigue damage, this work proposes an additional DT procedure that enables blade operability assessment without requiring complete load history data.

Protective coatings are applied to mitigate oxidation, corrosion, and thermal degradation; however, these coatings degrade over time due to thermal, mechanical and chemical load. Coating degradation can initiate fatigue microcracks that may propagate into the substrate, potentially leading to blade failure if undetected. While fatigue microcracks may already be present in blades after general overhaul (GO), the protective coating is required to be free of integrity defects (Fig. 1). Technical documentation specifies an allowable coating thickness range. If the coating is thicker than the upper limit, it may peel off during operation. If it is thinner than the minimum allowable limit, it may burn through. As the quality of the protective coating degrades during service, extensive coating loss can leave the substrate unprotected, leading to rapid damage and potential destruction of the blade material.

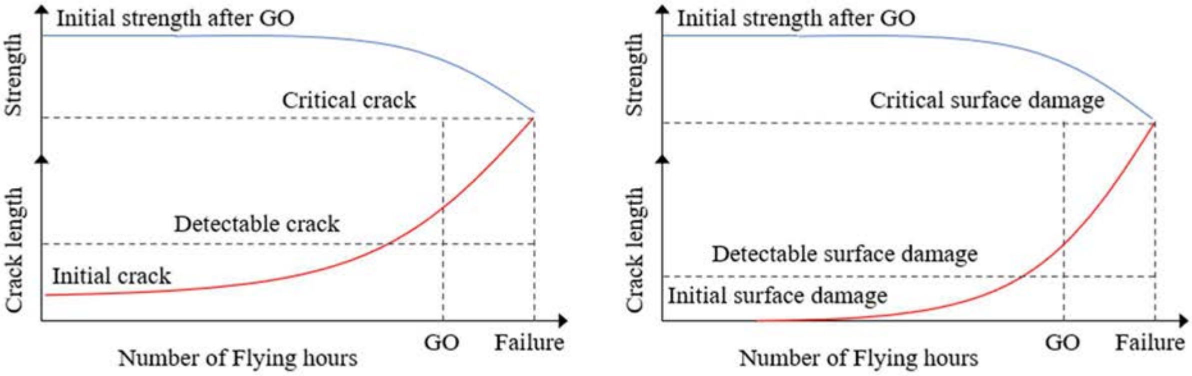

Fig. 1: Fatigue crack growth (left) and protective coating damage (right) during the service life

Several accidents have demonstrated the difficulty of identifying turbine blade damage mechanisms, highlighting the need for improved safety procedures. This article therefore proposes a DT oriented process based on image processing techniques to assess coating degradation, enabling earlier detection of critical damage and improved life management of helicopter engines.

2. Damage tolerance methodology

Damage tolerance is a key design and certification philosophy in structural engineering, ensuring that components can safely sustain a defined level of damage until inspection or repair (Howard, 1979; AFGROW). Unlike safe-life approaches, which assume defect-free structures, damage-tolerant design explicitly considers pre-existing defects such as microcracks, material inhomogeneities, or coating defects.

There are three basic types of rotor turbine blade damage during the service life. The first one is a fatigue crack. It is expected that this degradation can grow from the maximum allowable initial length a_{IN} to a length shorter than the critical crack length a_{CR} which would otherwise cause structural failure of the blade. The Time Between Overhaul (TBO) and GO procedures including visual inspection, Non-Destructive Testing (NDT) and a minimal safety limit defined by airworthiness standards (e.g. FAR or STANAG) ensure that no fatigue crack longer than a_{CR} can be operated after GO. An example of failure analysis of a turbine blade is described by Mishra (2017).

The second typical damage is high temperature corrosion. This type of damage grows from the surface to the substrate material and creates notch and material absence. From such an area a new fatigue crack can be initiated. During the GO the blades are cleaned from the old residual protective coating, then the blade is subjected to the visual check. No blade with this type of damage can be operated after GO but, in some cases, the damaged micro areas can be false negative defined. This type of degradation effect initiates the first fatigue microcracks in the substrate material leading to failure.

The third type of damage is the absence of protective coating. As in the previous type of damage, during GO the blades are cleaned from the old residual protective coating, then the blade is subjected to the visual and NDT check and then the new protective coating is applied. The proposed method suggests using a standard borescope procedure between the flights combined with automated microscopic image analysis to define the real state of surface damage. Such service data can be obtained, and the damage assessment can be defined.

3. Experiment

This chapter describes an experimental program focused on the turbocompressor second stage rotor blade of the helicopter turboshaft engine TV3-117 (Fig. 2). The blade structure consists of two different materials. Nickel alloy ZhS6K is the substrate material of the blade covered by a protective aluminium layer. Such designed blades should withstand aerodynamic pressure, centrifugal force, high temperature and exhaust gases. The chemical composition is defined by Swadźba (1992). The operational regimes, revolution and temperatures before the turbocompressor is defined by Furda (2016). Thirteen TV3-117 turboshaft engines and their turbine blades were subjected to visual and microscopic analysis. Digital microscopy analyses were performed using an Olympus DSX1000 optical microscope. Subsequently, the surface quality of the images was analyzed using image processing techniques in MATLAB to determine the surface integrity, defined as the percentage of residual protective coating.

Fig. 2: The turbine blade after the service life

Some helicopters are used for special missions, such as rescue or training. Even when the engine is operated within its operational limits, the blades may be subjected to higher than normal loads. One example is an immediate engine shutdown after first ground contact. In this case, outside air enters the hot engine, causing the blades to cool very rapidly. Such rapid cooling generates uneven and non-standard thermal loads, leading to increased stress and deformation, especially in the trailing edge region where the material thickness is minimal. Another example of extreme loading is an autorotation manoeuvre, which can cause abnormal heat distribution, especially when transitioning from hover mode, even if the helicopter is otherwise operating within its nominal limits.

4. Observation and results

Protective coating damage is classified into three basic categories. After GO, the blade surface is smooth and free of damage. During service, the first visually detectable material loss may occur. Major damage, characterized by large areas of missing protective coating, can rapidly lead to burn-out of the substrate material (Fig. 3).

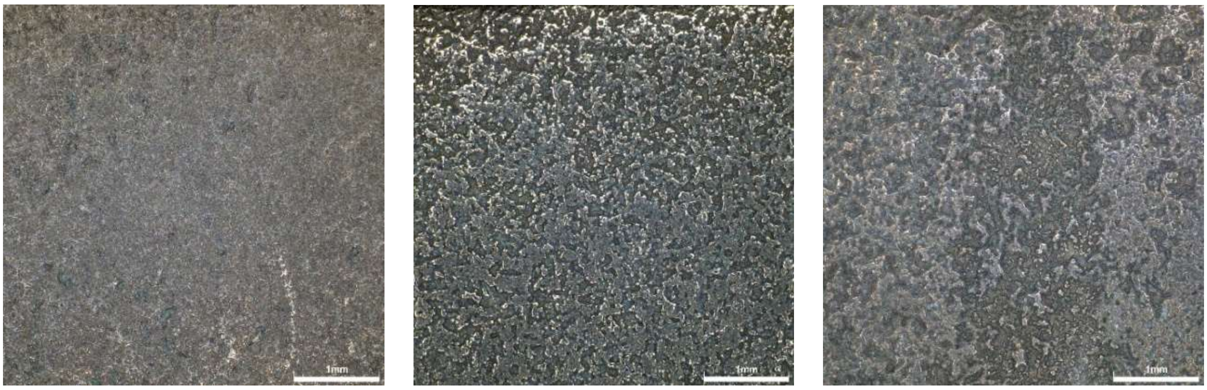

Fig. 3: The turbine blade coating damage during the service life: initial (after GO procedure including ground test: less than 1% coating damage - left), first visual detectable damage (after 520 Flight hours: 13% coating damage - middle), major damage (after 819 Flight hours: 32% coating damage - right)

The fatigue cracks initiated from protective coating damage are shown in Fig. 4. Several fatigue cracks are across the protective coating. In some areas the protective coating is damaged. Initial fatigue microcracks are also present in the substrate material.

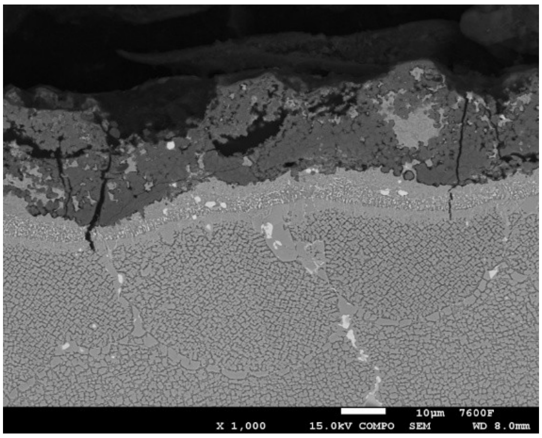

Fig. 4: The cross section of the turbine blade with first microcracks in the coating layer and substrate material (after 1132 Flight hours)

5. Discussion

Degradation of the protective coating leads to the initiation of fatigue microcracks in the substrate material of turbine blades, even when the visible surface damage appears limited. Critical regions include thin-walled areas such as the trailing edge, where non-standard operational events, including rapid engine shutdowns and autorotation manoeuvres, induce non-uniform thermal fields and elevated local stress concentrations. These conditions may result in significant subsurface fatigue degradation that remains difficult to detect using conventional inspection techniques. The proposed surface integrity–based evaluation captures the cumulative effect of such complex operational loading and enables its interpretation within a damage tolerance framework. The surface integrity parameter may thus be regarded as a surrogate damage metric linking observable surface condition with hidden fatigue risk, providing an additional decision criterion for blade operability in cases where complete operational load history is unavailable. This approach extends existing maintenance procedures by introducing a physically interpretable indicator of early fatigue damage initiation. The industrial aspects of this research will help predict potential hidden major damage and reduce the number of future helicopter accidents. The methodology is not limited to ZhS6K and may be extended to other turbine blade materials and operating regimes, contributing to improved reliability and safety of gas turbine engine components. Future steps will be focused on the numerical simulation and probabilistic approach of protective coating damage.

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References

Swadźba, L., Maciejny, A. and Formanek, B. (1992) Microstructure and resistance to cracking of modified Al-Si and Al-Cr diffusion coatings on ŻS6K nickel-based superalloys, *Surface and Coatings Technology*, 54–55, Part 1, Pages 84-90

Chmiela, B., Kianicová, M., Sozańska, M., Swadźba, L. (2012) Degradation of Si-Al aluminide coating after service of turbine blades made of ZhS6K superalloy, *IOP Conference Series*: Materials Science and Engineering, 35.

Howard, A. and Engle, R. (1979) USAF Damage tolerant design handbook: Guidelines for the analysis and design of damage tolerant, Report ADA078216, *Defence Tactical Information Center, U.S. Air Force*

AFGROW: Handbook for Damage Tolerant Design: https://www.afgrow.net/applications/dtdhandbook/, *Air Force Research Laboratory*

Mishra, K., E., et al. (2017) Failure analysis of an un-cooled turbine blade in an aero gas turbine engine, *Engineering Failure Analysis*, 79, pp. 836–844.