

FRACTURE EVALUATION OF IN-SITU SENSORS FOR HIGH TEMPERATURE APPLICATIONS

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ABSTRACT

The feasibility of fabricating an in-situ crack sensor for real-time detection of surface cracks propagating in engine components was evaluated using a computational fracture mechanics model. The in-situ sensor system would be required to: (1) be capable of sustaining normal function in a severe environment; (2) transmit a signal if a detected crack in the component was above a predetermined length, but below a critical length that would lead to failure; (3) act neutrally upon the overall performance of the engine system and not interfere with the engine maintenance operations. In this work, fracture mechanics methodologies are used to identify the requirements for an in-situ sensor system that could withstand the engine operating environment, foreign object damage, and minimally degrade engine performance. A computational fracture mechanics model was developed to evaluate the feasibility of fabricating an in-situ crack sensor for real-time damage propagation detection in engine components.

KEYWORDS: In-situ sensor, fracture, thin film, engine, high temperature, aircraft safety

INTRODUCTION

The engine fracture-critical part designation is given to those components with enough energy, due to high rotational speeds and mass, whose failure can have catastrophic consequences. Containment of these potential failures is unrealistic and is not a standard practice due to the excessive weight introduced by a robust containment system would introduce. Therefore, use of a light weight in-situ sensor capable of detecting impending failures will allow timely maintenance actions leading to an increase in overall safety. To implement an in-situ sensor system on an aircraft engine requires several hurdles to be overcome; the operating temperatures of aircraft engines typically exceed 500° C; foreign object damage (FOD) is prevalent in service and manufacturing environments; maintenance actions are driven by safety and cost so the sensor system must not require active attention; and the aircraft engine performance must not be degraded by the inclusion of the sensor, e.g. increased weight or interruption of the gas path.

Currently, high temperature rotating components are inspected visually during routine maintenance with an optical scope, and comprehensively inspected during overhaul using nondestructive inspection (NDI) such as eddy current and ultrasonics. Any new sensor methodology should not increase the frequency of overhaul due to the overwhelming cost of grounding aircraft. An in-situ sensor system, designed and implemented properly, would not require user interaction and may actually reduce the ground time of an aircraft, while increasing overall safety. Current research into in-situ sensor methods for rotating, high-temperature equipment is based on the eddy current method [1, 2]. A sensor capable of inducing eddy currents hovers over the rotating part and detects changes in the signal due to damage. However, these approaches are typically unable to physically monitor a large surface, the diagnostic signals gradually degrade with time, and long-term histories must be stored and analyzed [3, 4]. To address these limitations, a new sensor system must be defined that would function at a high temperature and not require the overhead of current systems. In this paper, the authors address the requirements for and propose a new sensor system based on recent advances in thin film technologies.

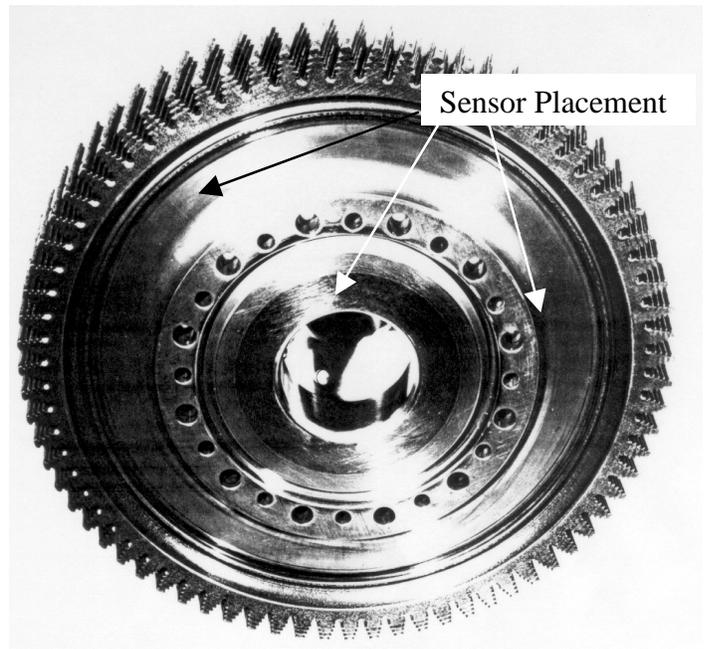


Figure 1: Component schematic and sensor placement location.

SENSOR REQUIREMENTS

An in-situ sensor system designed for high-temperature, rotating applications must conform to the following physical requirements (a schematic of an engine component and proposed sensor placement is shown in Figure 1):

- sensor cannot add significant weight to the structure
- sensor must sense impending component failure without “false alarms” due to FOD, light impact or manufacturing damage.
- coefficient of thermal expansion cannot vary significantly from the base material
- bond for an attached sensor must be able to withstand the thermal expansion of the component and the physical stress of rotation
- sensor must require little user interaction or local data storage
- sensor must not interfere with the continual operation of the engine
- sensor must be cost-effective and readily applicable in a manufacturing environment
- sensor must have tolerances consistent with component design

THIN-FILM SENSOR

Evaluation of current NDI methods and the previously mentioned sensor requirements leads to a sensor design based on thin-film technology. Thin films add little mass to the structure due to small volume; are designed for use in high temperature environments; and can be deposited on an existing structure within current manufacturing tolerances [5]. Choosing the proper material will enable the thin

film to act as an electrical device for sensing systems; absorb impact damage from FOD; and be less susceptible to corrosion than the base component [6]. Recent research in thin film sensors [7] points to tailoring the material properties, such as electrical impedance, to fit the application. For instance, a series of electrically conductive and nonconductive materials could be deposited upon a component. The topmost layer would be designed to withstand damage from FOD, corrosion, impact or manufacturing, and to protect the underlying layer, the conductive material, which would act as the sensor. Another layer would be designed to bond the conductive coating to the component and provide a smooth stress gradient between the sensor and component. An electronics package containing a remote transceiver could then be attached to the stationary portions of the engine to transmit and receive the electrical signals sent through the coating. The electrical system would generate a signal when the conductive material cracks and/or breaks causing an increase in the impedance.

A damage tolerance approach was taken to design the sensor system. First, the sensor must be attachable to the component (shown in Fig. 1). Thin film technology has developed a means of vapor deposition that deposits the coating on rough surfaces with favorable delamination properties [8]. The coating must also be within a given tolerance of the coefficient of thermal expansion (CTE) of the component. If the CTE is significantly different from that of the component, then the thermal cycling of the engine during operation will cause the sensor to delaminate. An idealized loading and temperature spectrum are shown in Figure 2.

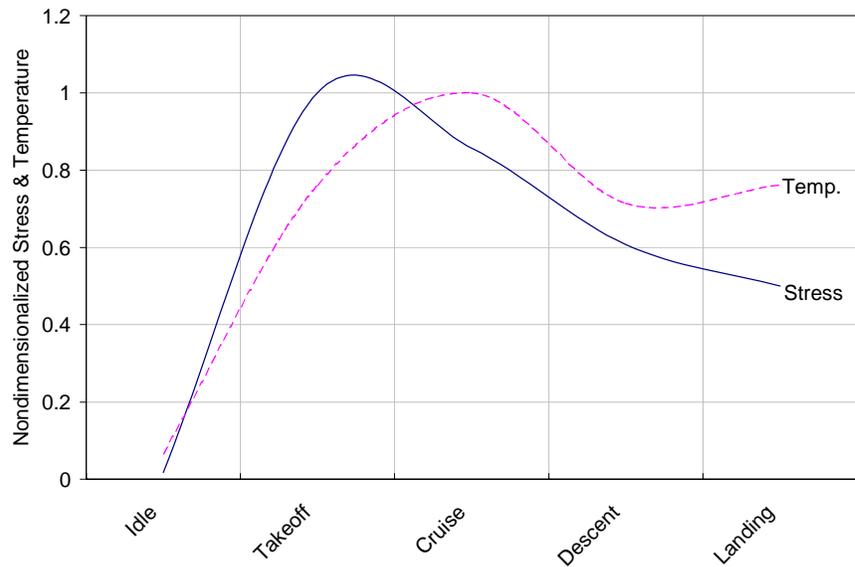


Figure 2: Idealized loading and thermal sequence.

A simple way for determining if this phenomenon will occur is to assume that the bond between the coating and the component behaves like a crack at a bimaterial interface [9]. If the stresses reach the point that a rogue void or crack stress intensity factor exceeds the local fracture toughness for the bond, then delamination occurs. Also, since the component is rotating, the centrifugal forces of the component must not cause the sensor to delaminate. The stress state at the interface was modeled using the finite element method, and the fatigue crack growth and delamination were modeled using a hybrid finite element/boundary element method [10]. A key advantage of this approach is that only the crack surface has to be discretized and remeshed during crack propagation, while the finite element model remains stable.

The sensor system is designed to generate a signal when a crack of a given size is present in the base component. A schematic of the system is shown in Figure 3. Tension is applied normally to the plane of the figure. It was apparent that the conductive layer of the sensor would need to be a series of wires, or grid, instead of a continuous layer. This was due to the elastic modulus of the insulating layer being higher than that of the conductive layer. As a crack approaches a more brittle material it will deflect [11]. This was evident because the wires are approximately the same thickness as the topcoat and insulating layer. However, the entire coating is much thinner than the component and does not experience this effect due to scale [12]. Therefore, delamination criterion, where the stress intensities at the interface exceed the fracture toughness of the bond, occurred frequently for all iterations of a crack

approaching the wire/insulation boundary [13]. Therefore, the wire mesh design was introduced to create a discontinuity in the crack path and further to be spatially adaptable to define the crack size resolution the mesh can detect. The wire endings are then connected to induction points that lay at the same radial and axial location along the component surface so that the induction element will hover above all of them as the part spins.

The sensor will consist of at least three layers deposited sequentially onto the surface of the component, as shown in Figure 3. The variables are defined such that: a_0 is the initial crack radius, c is the thickness of coating, d_c is the distance from the crack to the coating, s is the distance between wires, d_w is the distance from the crack center to a wire ($0.5 s$), h is the height of the wire from the base material, t_w is the thickness of the wire, w is the width of the wire, K_{Td} is the delamination fracture toughness of the sensor/base material bond (assumed to be $0.195 K_{T1}$), P is the applied load, $E_1, \nu_1, \alpha_1, K_{T1}$ are the Young's modulus, Poisson's ratio, coefficient of thermal expansion and fracture toughness for the base material, $E_2, \nu_2, \alpha_2, K_{T2}$ are the material properties of the coating and $E_3, \nu_3, \alpha_3, K_{T3}$ are the material properties of the wires.

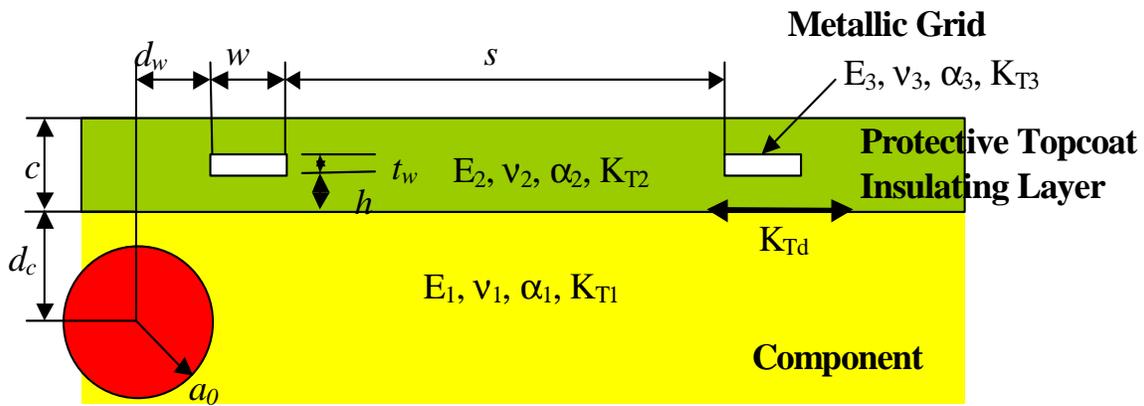


Figure 3: Definition of crack sensor system.

RESULTS

The finite element model was generated such that the displacements, physical and thermal loads (Fig. 2) were input such that the stress field at the crack was similar to that of a rotating engine component (Fig. 1). The initial crack radius was defined as a_0 , the base material (E_1, ν_1, α_1) and the wire mesh were assumed to be the same material (E_3, ν_3, α_3). The insulating and protective layers were also assumed to have the same material properties such that ($E_2 = 1.95 E_1, \nu_2 = 0.73 \nu_1, \alpha_2 = 0.89 \alpha_1$). The initial crack was located equidistant between wires such that the wire spacing would be minimized to detect a crack of a_0 as it propagated. Note that all spatial variables are nondimensionalized to the initial crack length, a_0 , and material variables are nondimensionalized to the component material (E_1, ν_1, α_1).

Design of the sensor system to withstand the service conditions (Fig. 2) of a rotating engine component involved determining the principal modes of system failure. The first mode investigated was the catastrophic delamination of the sensor. Initially, the thickness of the coating, c , and the spacing of the wires were varied to determine acceptable stress levels at the component-sensor interface to avoid rapid delamination. For this study, it was assumed that delamination occurred if the stresses at the interface (K_T) exceeded the fracture toughness (K_{Td}) of the bond. Once the onset of delamination was observed, the interface stresses were continually monitored during fatigue crack growth to predict delamination arrest ($K_T/K_{Td} < 1$), stable tearing ($1 < K_T/K_{Td} < 1.5$), or catastrophic failure ($K_T/K_{Td} > 1.5$) [14]. The trend of a thinner coating producing less delamination stress is clearly illustrated in Figure 4.

Also, decreasing the spacing of the wires in the sensor reinforces the system in a manner similar to fibers reinforcing a composite, also depicted in Figure 4. Therefore, the sensor is less prone to delamination if the coating thickness does not exceed $0.166 a_0$, and the wire spacing is less than $1.10 a_0$.

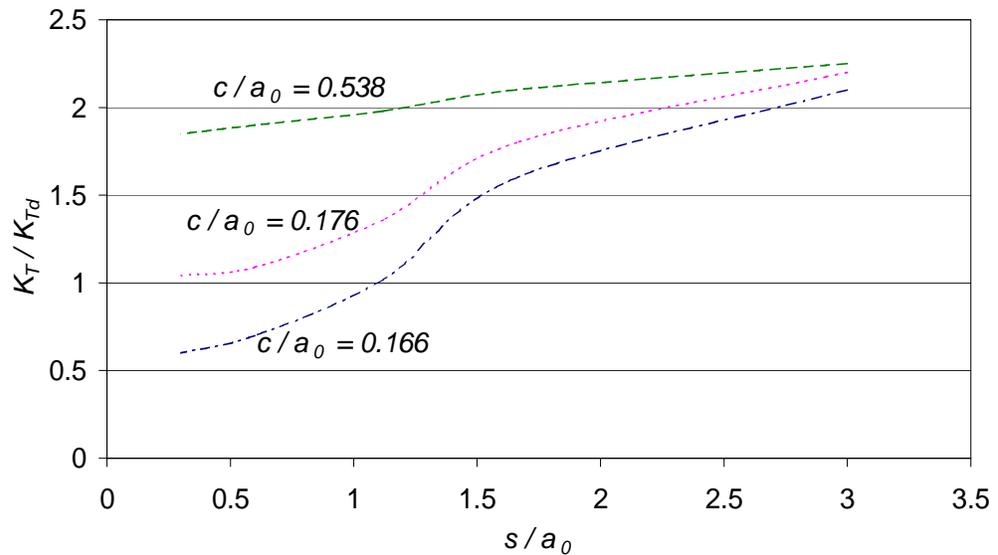


Figure 4: Effect of coating thickness and wire spacing on delamination.

The second mode of failure investigated was fracture of the sensor system due to the fatigue cracking of the component. The sensor material is quite brittle, e.g. a lower fracture toughness, K_{T2} , in comparison to the component material, K_{T1} , and will therefore fracture at a lower stress. The key factors in preventing fracture of the sensor are the position of the wire in the mesh and the size of the crack as it approaches the sensor. If the wire is placed too close to the surface, the insulating layer will simply crack and fall off as the fatigue crack propagates through the part, while the wire remains intact. If the wire is placed too close to the part, then the fatigue crack will break through the insulating layer between the part and the wire causing delamination to occur at the interface. Therefore, the wire in the sensor must be embedded within the coating a minimum of 20% of the coating thickness from either side, as illustrated in Figure 5. This minimum must be then raised to 25% to provide adequate electrical insulation between the component and wire.

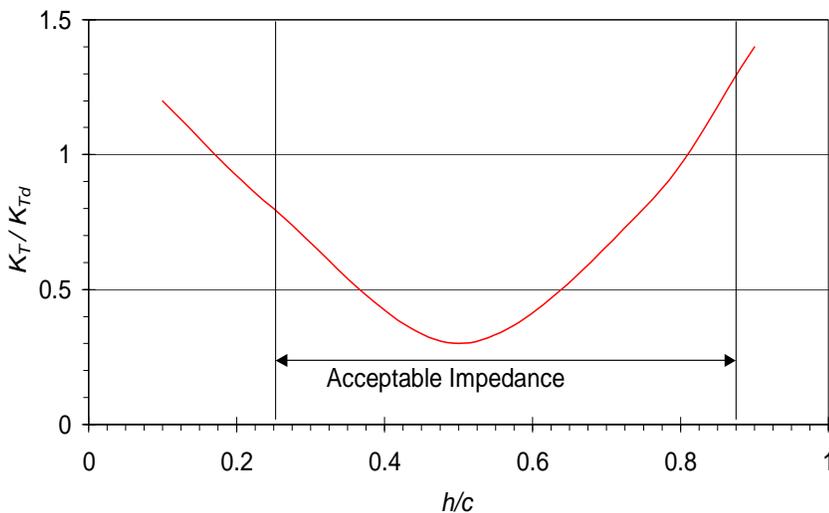


Figure 5: Effect of wire placement on impedance and initiation of delamination.

CONCLUSIONS

The fracture mechanics modeling has shown that it is possible to design a patterned coating on the engine component surface which will be adherent at the stresses and temperatures normally present in operation, and will fracture in a controlled manner when, and only when, there is an underlying crack in the disk. The model has predicted an upper boundary of $c/a_0 = 0.175$ for the total coating thickness, of which at least 25% must be the protective layer covering the conductive grid. Although the model

predicts improved mechanical performance with thinner insulating and metallic layers, the minimum acceptable thicknesses are determined by the required electrical properties of the metallic grid. All the electronic concepts studied required that the insulating film between the component and wires be on the order of $c/a_0 = 0.04$ or greater so that the sensor would have an acceptable impedance. Although the work to date has shown that the proposed sensor is viable, many challenges lie ahead before such a sensor can be demonstrated in an operating engine.

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