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# THE CRACK-DETECTED COATING SENSOR AND ITS APPLICATIONS IN R&M OF AIRCRAFTS

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## Abstract

*A fatigue crack monitoring method called ICM (Intelligent Coating Monitoring), which is based mainly on the intelligent coating sensor, has the capability to monitor crack initiation and growth in fatigue test coupons has been suggested in this study. The intelligent coating sensor is normally consisted of three layers: driving layer, sensing layer and protective layer where necessary. Fatigue tests with ICM for various materials demonstrate the capability to detect cracks with* $l<300\mu m$*, corresponding to the increment of the sensing layer's resistance at the level of* $0.05\Omega$*. Also, ICM resistance measurements correlate with crack length, permitting crack length monitoring. Numerous applications are under evaluation for ICM in difficult-to-access locations on commercial and military aircrafts. The motivation for the permanently flaw-detected coating monitoring is either (i) to replace an existing inspection that requires substantial disassembly and surface preparation (e.g. inside the fuel tank of an aircraft), or (ii) to take advantage of early detection and apply less invasive life-extension repairs, as well as reduce interruption of service when flaws are detected. Implementation of ICM is expected to improve fleet management practices and modify damage tolerance assumptions.*

## 1 Introduction

Reliability and maintainability of an aircraft is not only the survival probability for aging aircraft and its infrastructures but also an important property of the aircraft and an important factor in determining the cost of life period for the newly constructed ones. More efforts are now being devoted to enhance the implementation of technologies and methodologies for structural health monitoring (SHM) of aircrafts. One of the authors has performed a large amount of researches on the evaluation of carburized gears considering the characteristics of crack growth based on fracture mechanics[1]. The innovative principles and new measures of SHM, which was applied in the aircraft, can provide technical support and guidelines for reliability and maintainability. As a result the efficiency and quality of the operating aircraft can be improved, and the total cost can be reduced. It is easily and efficient to monitor the position of fatigue damage and spreading of crack where the ideal SHM technology used, then evaluate the structural security and forecast structural life of aircrafts. But the accumulation of fatigue damage in critical structural components of operating aircrafts, especially aging ones remain in service, is an increasingly complex and continuing high priority problem. In order to ensure the integrity of aircraft structures, the detection, monitoring and analysis of fatigue cracks still play an important role today, and will do so in the foreseeable future. A method for continuously monitoring fatigue crack initiation is considered necessary to the investigation on the fatigue crack initiation life and very valuable in preventing accidents in machinery as well. Many studies have been performed on the detection of fatigue crack initiation. Makabe et al.[2] used a strain waveform for the detection of fatigue crack of 0.5-1mm on a round test piece with a small hemispherical pit. Katayama et al.[3] and Lee and Sakane[4] detected crack initiation using an AC potential method on a sharply notched test piece. Tohmyoh et al.[5] detected the fatigue crack initiation of a test piece with a surface slit during rotating bending tests using surface shear-horizontal waves. Papazian et al.[6] and Zilberstein et al.[7] performed many studies on the application of a meandering winding magnetometer array sensor, ultrasonic techniques, and an electrochemical fatigue sensor for the detection of crack initiation for many different types of fatigue test pieces. Methods which involve the inspection of structures for cracks or flaws, without long term monitoring, are generally termed NDT (non-destructive testing) techniques such as X-ray diffraction, ultrasonic wave distortion, laser diffraction, infrared thermography, acoustic microscopy, and positron annihilation. At the same time, new techniques which differ from NDT, have been developed to monitor structures for cracks or flaws over a long period of time. One of these is called ICM[8,9], or Intelligent Coating Monitoring. This technique provides a novel and exciting method for crack initiation detection, and long term monitoring of fatigue cracks in aircraft structures.

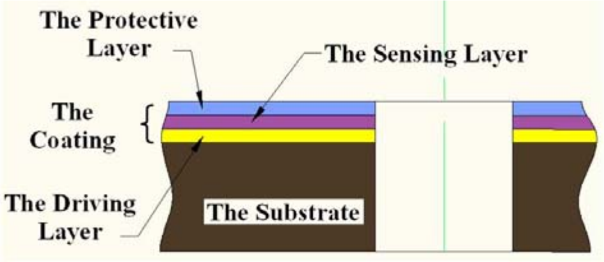
This study will briefly explain (i) the principle of ICM technology, (ii) its current sensitivity and reliability for crack detection on material surfaces and within lap joints during fatigue tests, and (iii) applications in Full Scale Fatigue Test of aircrafts.

## 2 Working Principle

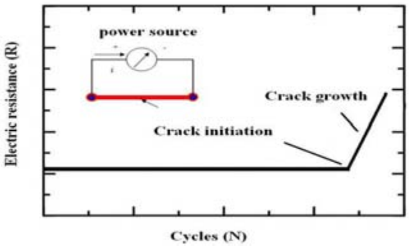
Intelligent coating is a new kind of functionally gradient material, which is characterized by thin film material with special effect. As shown in Fig.1 (a), the intelligent coating is consisted of three layers: the driving layer, the sensing layer and the protective layer, respectively.

The driving layer is made up of nonconductive materials and plays two roles: on the one hand, crack will appear on the driving layer when the substrate is getting crack, and will force the sensing layer to split at the same time; on the other hand, the driving layer spaces out the substrate and the sensing layer with good insulating efficiency in conformity to the requirement of the design. The sensing layer is normally made up of conductive materials such as Cu, Ag, C, etc and can represent the crack length in substrate by its resistance variation. The process of nano-Cu was applied to manufacture the sensing layer in the present study. It should be pointed out that both the driving layer and the sensing layer are very thin, not more than 20μm normally. In this study the thicknesses of the driving layer and sensing layer are about 20μm and 15μm, respectively. Meanwhile, the width of the sensing layer is 1mm. The protective layer which is fine in strength, hardness, anti aging property and anticorrosion performance at minimum thickness will be provided for the intelligent coating, and it plays a very important role in the manufacturing, installation and application process of ICM sensor.

The ICM sensor is about several tens of micrometers, so a small surface crack will cause the sensor to crack, a special feature designated as synchronous damage characteristic, and the electric resistance to increase, as shown in Fig.1 (b). The starting point of the increase in the electric resistance of the sensor corresponds to the instant of the crack initiation. Therefore, the health status of the substrate (or structure) can be denoted by the variation of the physical properties of the intelligent coating. The variation of the conductive resistance of the sensing layer was applied to detect the crack size and crack propagation in this study. The method of ICM is a very simplicity and stably measurement system, which consists of a DC power source, an electric resistor and a data recorder.



(a)



(b)

**Fig. 1. A Schematic of the Intelligent Coating**

## 3 Experimental details

Three kinds of materials have been applied for this research, which are 4340M steel, 7074 aluminum alloy and TC4 titanium alloy, respectively. Five types of specimens including riveted lap joint and screwed connection were tested, as shown in Fig.2. In this experiment, all the intelligent coatings were in-situ manufactured based on nano-technical process of materials and the sensing layers were consisted of nano-Cu. The thickness and the width of the sensing layer are about 15μm and 1mm, respectively.

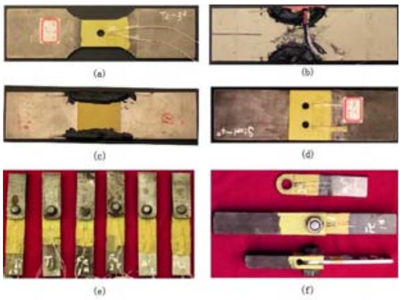
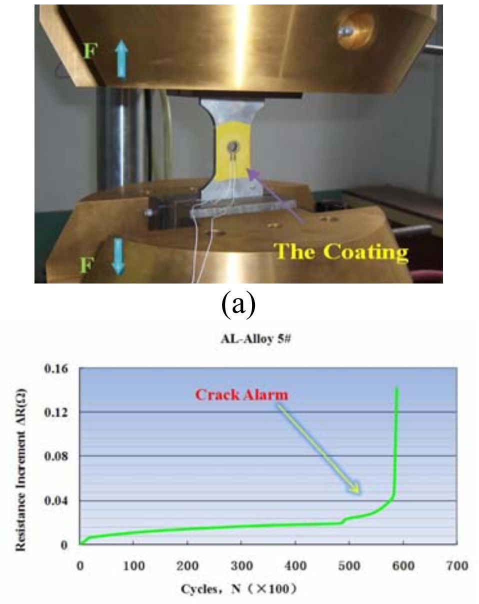


**Fig.2. Test specimens**

Fatigue tests have been carried out for each kind of test specimens to determine the ability of the developed intelligent coating to measure initiation and propagation of fatigue crack less than 1mm on surfaces and within lap/butt joints.

## 4 Results and discussion

Fig.3a shows fatigue test of 7074Al specimen with one-side ICM monitoring, and the resistance variation of intelligent coatings versus the load cycles are depicted in Fig.3b. This specimen was fatigue loaded with 15 Hz, load ratio R=0.2 and the maximum tension load P=18KN. The first crack was detected after about 58000 cycles if we set the alarm value ΔR as 0.05Ω. At this stage the test was stopped and the specimen was fractured with a secondary loading so that the crack length on the fracture surface could be measured and verified by stereoscope. It is found the crack length is about 0.3mm corresponding to ΔR=0.05Ω.

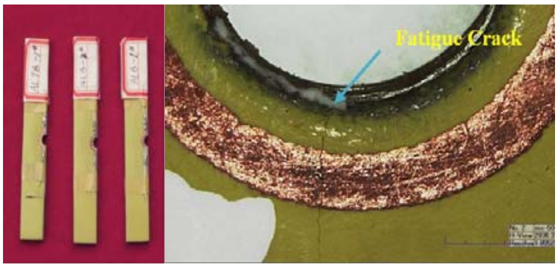


(a)

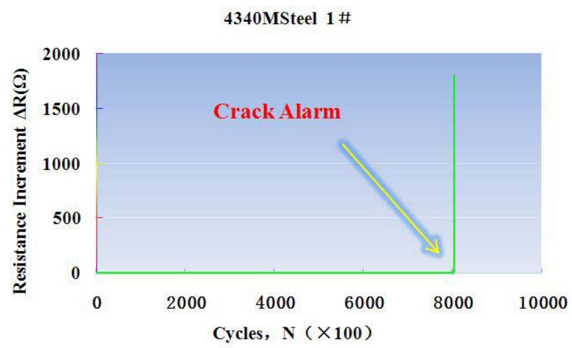
(b)

**Fig. 3. Fatigue test of aluminum alloy specimen and plot of ICM system output versus load cycles**

Influence of different loading methods (such as tension-tension, tension-pressure and three point bending) on fatigue behavior of ICM has also been investigated in this study. Fig.4a shows three point bending specimens of 4340M steel and the fatigue crack. According to the experimental data of resistance increment and cycles that has been shown in Fig.4b, it could safely draw the conclusion that the crack length is about 0.3mm corresponding to ΔR=0.05Ω. The growing resistance of ICM appears continuously graded changes in the crack growth initial stage and increase rapidly at the final stage of crack propagation.



(a)



(b)

**Fig. 4. Fatigue test of three point bending specimen and Plot of ICM system output versus load cycles**

Similar results have been achieved with other specimens. Particularly, ICM sensors can monitor the riveted lap and butt joints where the fatigue cracks normally commence at the hole edges. For example, test results for specimens as Fig. 2e (double-side monitoring) are shown in Fig. 5. It is found the crack length is about 0.3mm corresponding to $\Delta R=0.05\Omega$ as well. Nevertheless, traditional methods, such as visual inspection, can not detect the initial fatigue cracks in closed construction. By the way, the fatigue crack was generated from the back face of the specimen and this phenomenon has been monitored by our developed ICM system, as shown in Fig. 5 and Fig. 6.

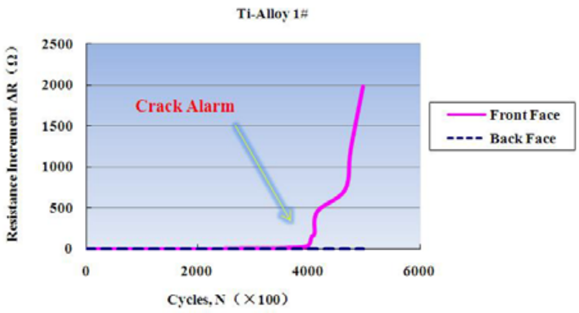


**Fig. 5. Plot of ICM system output versus load cycles for lap/butt joints**

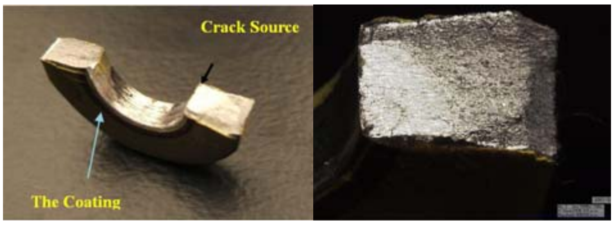


**Fig. 6. Fracture surfaces of lap/butt joints**

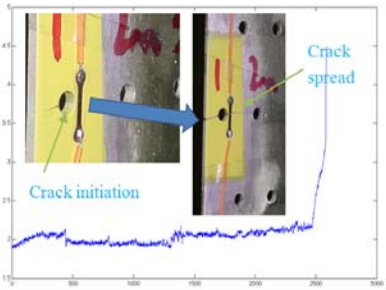
The experiment results presented in above suggest that the intelligent coating can be used to detect small fatigue cracks and monitor their growth. This capability can be used for early stage diagnostics and for prognostics, i.e. assessment of how long a component can operate safely and when it should be reinspected. When required, the intelligent coating can offer a reliable permanently monitoring tool for fatigue damage detection at critical locations, which are difficult to access for inspection. Furthermore, when local small cracks can be detected reliably in fatigue critical locations, the contribution of life extension could provide a direct effect of major cost reduction by local rework and maintainance. Following rework, the ICM could provide continuous or frequent periodic monitoring of repaired locations. This is very useful both for the safety of aging aircraft and the design of new aircraft.

## 5 Application of ICM

The influence of structural aging and the dangerous combination of fatigue and corrosion, coupled with recent accidents in civil structures and military facilities, has produced a greater emphasis on the application of active structural health monitoring systems. The costs associated with the increasing maintenance and surveillance demand of aging structures are rising. Thus, aircraft and spacecraft manufacturers have realized that they would like to use more integrated automated inspection systems provided that they do offer a beneficial cost and possibly are more reliable when compared to current inspection methods. Based on this demand, ICM, a real-time sensor system, has been developed to prevent unexpected flaw growth and structural failure of aircraft. Through the use of these in-situ sensors, it is possible to quickly, accurately and remotely monitor the integrity of a aircraft in service and detect incipient fatigue damage and flaws before catastrophic failures occurs. Following is a brief description of some potential applications in order to demonstrate the range of uses for this technology.

## 5.1 Application on fatigue crack monitoring

Fatigue crack and corrosion are the main damage patterns of the aircraft structure and the most serious damage. Actual aircraft structures of aviation put forward high demand for structural fatigue crack monitoring system as the aircraft structure trend towards maximization, complication, high reliability and harsh operation environment. ICM system can be used to directly detect the onset of crack of key dangerous positions and difficult-to-access locations such as tank, wing structures, leading edges, thrust structure and main landing gears. Large area structural component and new formation of fatigue crack (multiple site damage (MSD) or widespread fatigue damage (WFD), important concern in aging aircraft especially) require distributed sensors and adequate monitoring accuracy to give minimum crack size for timely maintenance. In 1988, a Boeing 737 aircraft lost a part of fuselage skin structure owing to multiple fatigue cracks in spar splices which was caused by multiple site fatigue damage especially in lap joints of the pressurized structure10. Therefore, current maintenance operations of aircraft in service require maintenance personnel to detect difficult-to-access areas to perform nondestructive inspections in harsh environment. In order to ensure the inspection and flight safety, the maintenance worker must remove structure, sealing priming paint, sealant and restore them. These disassembly processes are not only time consuming but also may induce new structural damage to the inspective areas. Therefore, the application of ICM sensor can overcome inspection impediments which have been mentioned above and improve the security of maintenance obviously.



(a)

(b)

**Fig. 7. (a) Fatigue test of assembled specimen and Plot of ICM system output versus load cycles (b) ICM system interrogation unit**

Fig.7 shows fatigue test of assembled specimen and ICM system on monitoring the propagation of the crack. It is found the crack initiation is beginning at 248,000 cycles corresponding to length of crack is about 0.3mm. The crack tip position did not get to the sensor through visual inspection and the ICM system interrogation unit did not detect the crack as well. But when the crack tip position through the sensor at 250,000 cycles, the growing resistance of ICM sensor appear continuously graded changes in the crack growth initial stage and increase rapidly at the final stage of crack propagation. At the same time, the alarm LED light of interrogation unit changed from green to red and remain on alarm state even after the crack is closed, as shown in Fig7(b).

## 5.2 Application on full scale fatigue test

Full scale fatigue test plays a significant role in determining the service life and damage development of aircraft. Traditional technical methods such as NDT, X-Ray, and AE (acoustic emission) and etc. have certain restriction in monitoring fatigue damages of aircraft critical structures during full scale fatigue test. According to the mechanical analyses, the intercostal web hole of central wing is very liable to appear fatigue failure and the position is difficult to access for non-destructive inspection when filled with water or oil as a leakproof fuel cell. However, the ICM technique can be applied to monitor the fatigue cracks in this area over a long period of time. Fig.8 shows ICM sensors mounted on central wing of a full scale fatigue testing aircraft to measure flaws. The sensor is placed between two repaired Al-alloy parts with a piece region of rivets. This real-time distributed ICM sensor network can find out damage status of key dangerous position where is sufficiently instrumented in test process. Therefore, it is reliable and stable to apply this autonomous health monitoring system in detecting the incipient damage and taking measures to rapidly expanded fatigue crack.

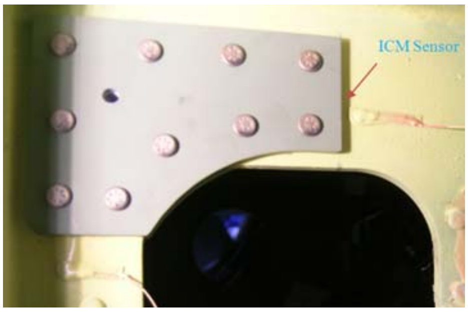


**Fig.8. ICM Sensors Monitoring on Central Wing**

## 6 Conclusions

This study has presented a crack length measurement method using the ICM sensor with a thickness of several tens of micrometers based on the change in the electric resistance of the sensor.

(1) The ICM sensor is sensitive to surface fatigue cracks and can be applied to detect cracks as small as 0.3mm mounted on surfaces or within lap joints in steels, aluminum alloys and titanium alloys.

(2) The measuring system based on the developed intelligent coating provides the capability for continuous on-line monitoring of crack initiation and growth during fatigue tests.

(3) Potential application prospect and its great significance of ICM sensors has been discussed on aging aircraft and full scall fatigue test to monitor crack initiation and growth. Extensive environmental testing and evaluation of system configurations is recommended prior to this application.

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