APPLICATION OF ELECTRIC POTENTIAL METHOD ON MONITORING FATIGUE CRACKING OF AIRCRAFT STRUCTURAL ELEMENTS

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Abstract

In this paper, the principle of electric potential method for monitoring crack was introduced. On the basis of this method, a set of experiments with the aluminum foils film were carried out for validating its feasibility, and then a typical aircraft structural element--middle-hole LY12-CZ plate specimen was employed here to simulate the process of the fatigue crack propagation of the aircraft structural element. Finally, curves and formulae about the relationship between voltage values and crack length value were obtained from the results of these experiments.

From these curves and formulae, we could find that a certain crack only corresponds with a set of certain voltage values, and vice versa. And it is possible to recognize and monitor the fatigue cracking position and crack length on the aircraft structures exactly through the electric potential method.

1 Introduction

The reliability of aircraft structure is a focal point that people always pay attention to[1]. The initiation and propagation of fatigue crack is the main damage pattern of failures in aircraft structures[2]. According to statistic, there are 80 percent failures in the aircraft-structure problems attributed to the reason of fatigue damage.

It is common phenomenons that fatigue cracks often begin from the surface, and then propagate in the structure gradually. Fatigue crack will induce the structural carrying capacities to decline and finally cause the structural failure. Therefore, the key to ensure the safety of the aircraft structure is to find the fatigue crack initiation in time and monitor its propagation effectively.

The routine NDT methods, such as ultrasonic testing method, magnetic particle testing method, eddy current testing method, radiographic testing method, and so on, only can be used for large size components [3,4]. These methods only suitable for static structural health monitoring, but are not suited to the structure health monitoring of real-time and online.

However, electric potential method can be much more easily and effectively in monitoring the state of the structural integrity [4~8]. With the rapid development of surface engineering technology, the preparation of high-performance coating which is conductive or insulating and has the ability to resist abrasion, fatigue and corrosion, has become possible[9,10]. So in this paper the electric potential method combined with surface engineering technology is employed to monitor fatigue cracking.

2 Methodology

2.1 Brief Introduction of the Principle of Electric Potential Method

Electric potential method is also called conductivity method, which is based on the conductive capability of the metal. Electric field will appear in the metal when an electric current transflux it. This electric field will change if fatigue crack occurs. The crack location, shape and scales may have different impact on the electric field, which is shown as different electrical potentials (U) or different resistances (R). As a result, it is possible to get the information about the crack through observing the changes of the electric potential.

For the reason of accompanying injuries, the corresponding cracks will also occur at the coating when the cracks initial from the surface of the structures. So we can prepare a special electric coating on the surface of the structure at first, and then monitor the origination and propagation of fatigue crack in the structure through observing the changes of the electric field in the electric coating.

2.2 Experiment Design

2.2.1 Experiment on Aluminum Foils Film

The characteristics of aluminum foil film and surface coat is similar; they are also conductive, filmy and homogeneous. At the same time, aluminum foils film is easy to cut into various shapes and make various cracks. Therefore, the aluminum foils film is chosen here to performing the simulation of the validating feasibility of electric potential method in monitoring the cracks.

2.2.2 Experiment on LY12-CZ Plate

We used a typical aircraft structural element--middle-hole LY12-CZ plate specimen, which is widely used in aviation field, as our research object to validate feasibility of electric potential method in monitoring the fatigue cracks in practical aircraft structural element.

First we prepare a nonconductive layer on the specimen by anodic oxidation technology, and then prepare an electric coating upon this layer by hot spraying technology. Finally, studies of monitoring fatigue cracking in the specimen using electric potential method will be carried out.

3. Application Electric Potential Method on Monitoring Crack of Aluminum Foils Film

On the discussions above, here we analysis relation between the electric potentials and cracks on aluminum foils film, in order to validate feasibility of electric potential method in the monitoring cracks.

3.1 Experimental Method

The experimental steps are described as follows:

(1) Make the film into a foursquare specimen as shown in the Fig.1. Every side of it is 4cm in its length.

(2) Let the electric current pass into the specimen from point A and pass out from point C. The current value is 3.00A.

(3) Make artificial penetrable cracks with different lengths respectively from point E, F, G, H, and J along the aspect, which is perpendicular to side AB. The cracking positions are shown in Fig.1. The length values of sections AE, AF, AG, AH, and AJ are 0.4cm, 1cm, 2cm, 3cm, and 3.6cm respectively.

(4) Respectively measure the voltage values U_{AB}, U_{AD}, U_{AC}, U_{DC}, U_{BC} and U_{DB} corresponding to different crack length values. And then curves about the relationship between voltage values and crack length can be drawn.

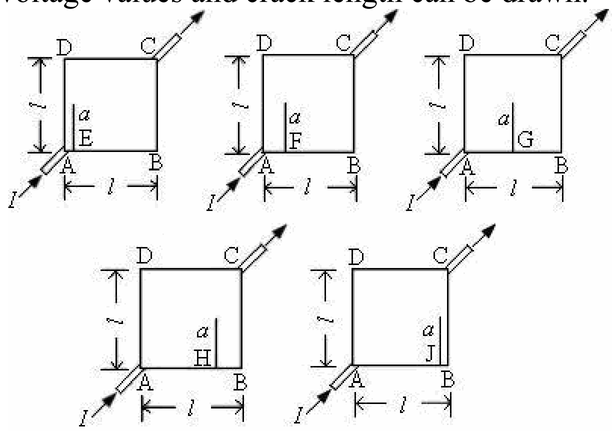


Fig.1 Aluminum film specimens with cracks and invariable direct current direction

3.2 Experimental Results

Based on the experimental method above, a lot of voltage values on specimens with different crack lengths and positions have been tested. Curves about the relationship between voltage values and crack length values with different position have been obtained, which are shown in Fig.2-Fig.7.

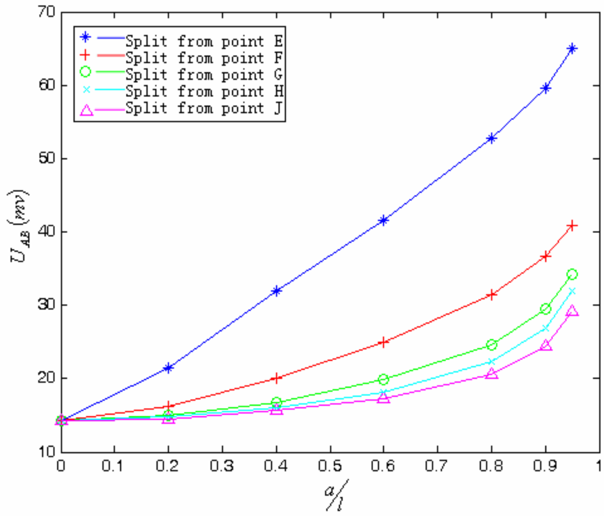


Fig.2 The Relationship between U_{AB} and a/l

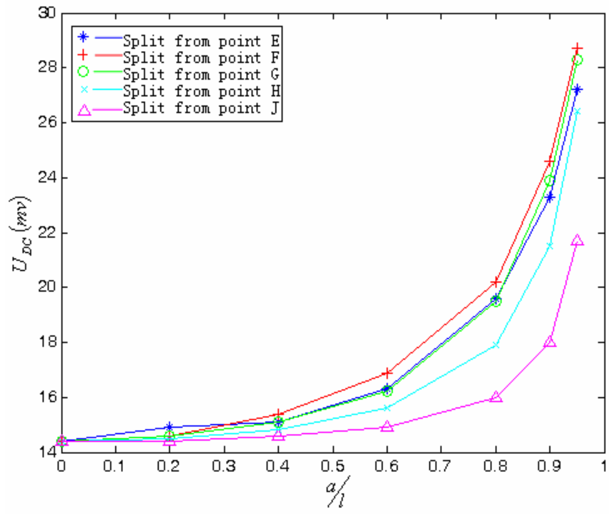


Fig.5 The Relationship between U_{DC} and a/l

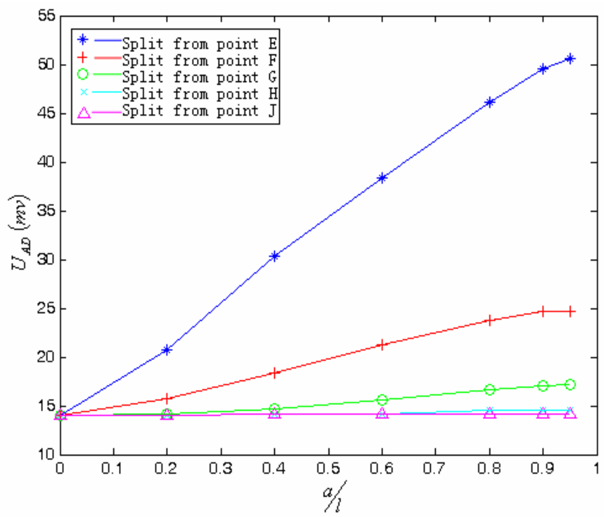


Fig.3 The Relationship between U_{AD} and a/l

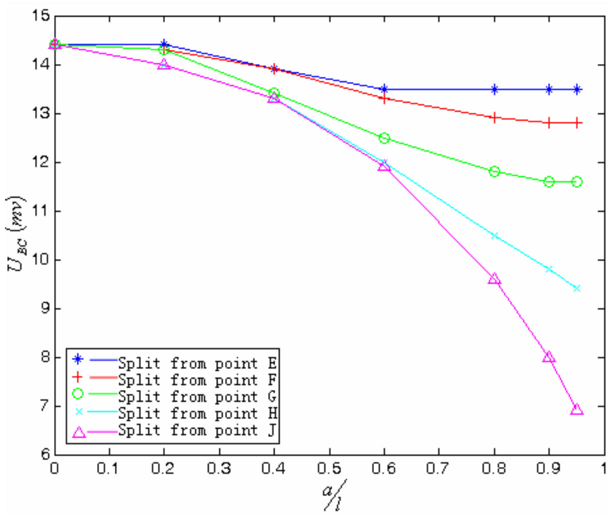


Fig.6 The Relationship between U_{BC} and a/l

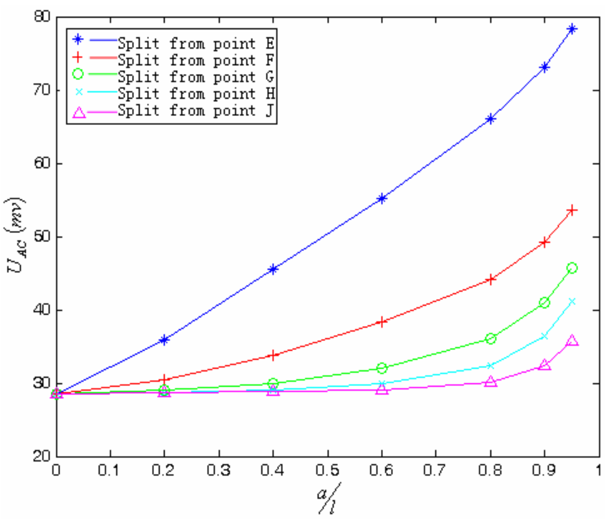


Fig.4 The Relationship between U_{AC} and a/l

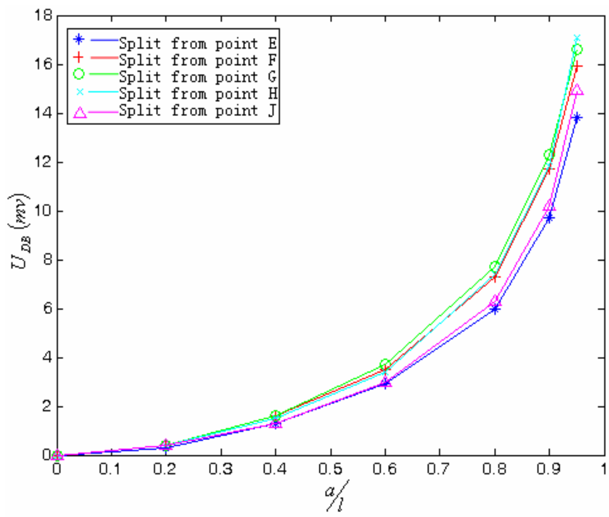


Fig.7 The Relationship between U_{DB} and a/l

From these curves, we can see that the voltage values (U_{AB} U_{AD} U_{AC} U_{DC} U_{BC} U_{DB}) will change when the cracking positions or lengths' value changes. And the set of voltage values (U_{AB} U_{AD} U_{AC} U_{DC} U_{BC} U_{DB}) will not be all the same when the cracks are different. That is to say, a certain crack only corresponds with a certain set of voltage values (U_{AB} U_{AD} U_{AC} U_{DC} U_{BC} U_{DB}), and vice versa.

So we can use a set of values (U_{AB} U_{AD} U_{AC} U_{DC} U_{BC} U_{DB}) to describe and recognize the cracking position and crack length exactly.

3.3 Conclusions

Electric potential method can be used to monitor the crack of aluminum foils film, if only we can measure a set of voltage values between some points, which are on the tested film.

If the shape of the film and the current value are certain, the voltage values we measured are only related to cracking position and crack length value.

For fatigue cracks always occur on the surface of components, if we cover the surface with an electric coating, this method can also be used to monitor the surface fatigue crack of components too.

4 Experimental Research on Monitoring Fatigue Crack in Aluminum Alloy Specimen

4.1 Specimen Preparation

A typical aircraft structural element--middle-hole LY12-CZ plate specimen shown in Fig8, was employed here as the research object to validating feasibility of electric potential method in monitoring the fatigue cracks in practical aircraft structural element.

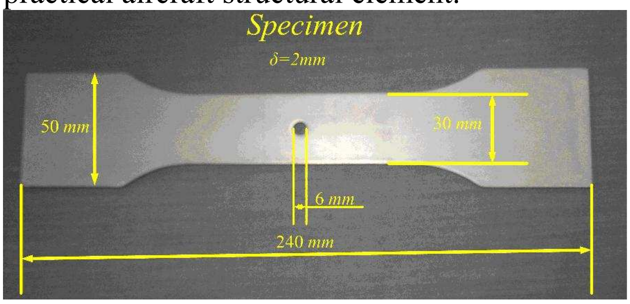


Fig.8 Aluminum Alloy Specimen

From the analysis in the second part of this paper, we know that there are two steps we have to do before the fatigue experiment. First, we should make the surface of the specimen nonconductive, and then cover an electric coating on the top of it. Here we have to emphasize that the shape of the electric coating should be regular, so that it could be possible to monitor the propagating crack through testing a certain set of voltages on it.

4.1.1 Nonconductive Layer Preparation

In order to make sure that only a special area on the specimen's surface is electric, we should make a nonconductive layer on it at first.

Since the specimen is made of aluminum alloy LY12-CZ, we can get the nonconductive layer by anodic oxidation technology. This disposal can make the entire surface of the specimen covered with a thin but compact oxide film, which is nonconductive.

The basic process of anodic oxidation technology is shown in Fig.9.

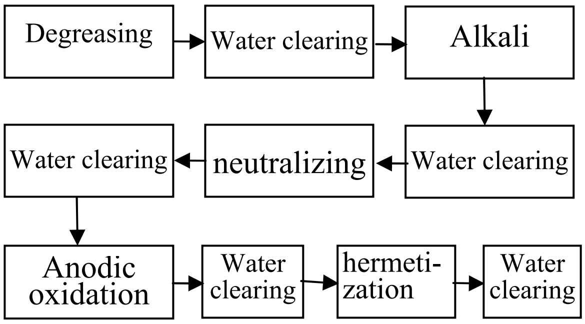


Fig.9 Process of Anodic Oxidation

Here we took the anodic oxidation method to get the nonconductive layer. The parameters are shown in Table 1.

Table 1 Anodic Oxidation Parameters

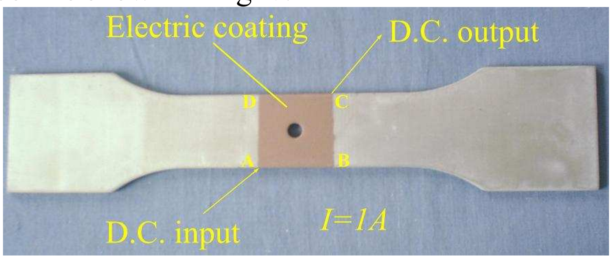
H_2SO_4	(g/L)	150~220
Al^{3+}	(g/L)	<20
Temperature	(℃)	13~26
DC Voltage	(V)	12~22
Density Current	(A/dm2)	0.8~2.5
Time Horizon	(min)	20~60
Cathode Material		leading
Ratio of Cathodic to Anodic Area		1~1.5:1
Stirrer Mode		Air Stirrer

4.1.2 Electric Coating Preparation

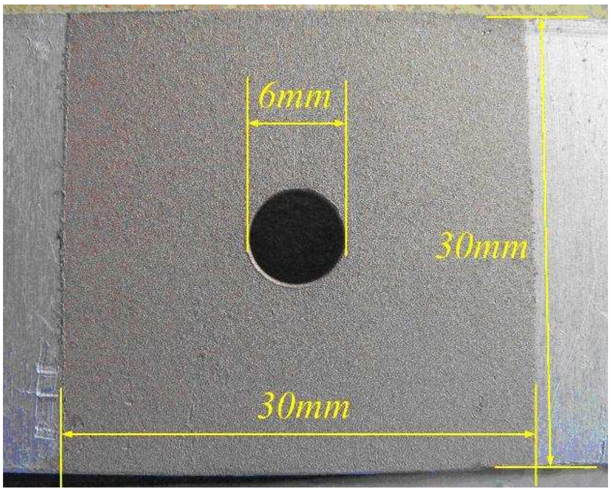
After getting the nonconductive layer, now we need to produce an electric coating on it.

It is very important to make sure that during the process of preparing the electric coating the nonconductive layer is not damaged. Here we chose not a chemical but a physical method--hot spraying technology.

Here we covered the monitoring-area of the specimen surface with a special kind of electric powder. This powder is made of cuprum mixed with argentums. The thickness of the electric coating is about 30μm; every side of it is *30mm* in its length; and the resistance of it is less than $0.5\Omega/cm^2$. The shape of the electric coat is shown in Fig10.



(a) Specimen with Electric Coating



(b) The Shape of Electric Coating

Fig.10 The Electric Coating

4.2 Fatigue Experiment and the Crack-monitoring Results

Before the fatigue experiment, a set of voltages were obtained. Here we let the electric current pass into the specimen from point A and pass out from point C, as shown in Fig.10. And the current value is 1.00A.

The values of the voltages along with the crack length are given in Table 2.

Table2 Voltage Values before Fatigue Experiment

specimen	U_{AB}	U_{AD}	U_{AC}	U_{DC}	U_{BC}	U_{DB}
No.7	0.188	0.194	0.396	0.198	0.204	-0.006
No.11	0.230	0.240	0.476	0.232	0.241	-0.008
No.13	0.214	0.218	0.461	0.242	0.244	-0.003

We can find out that during the fatigue experiment the crack will definitely appear at the edge of the hole on the specimen. So we considered that an initial crack is in the specimen, and the length of which is diameter of the hole (6*mm*), for the convenience of the later experimental result analysis.

4.2.1 Fatigue Experiment

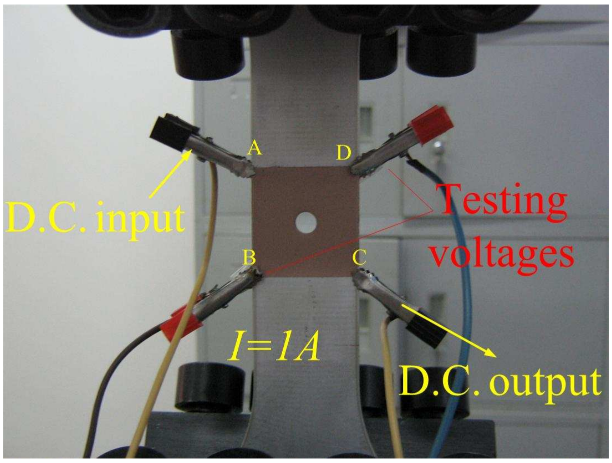
Here we divided the fatigue experiment into two parts. One is prefabricating initial fatigue crack, and the other is the crack propagation.

4.2.1.1 Prefabricating initial crack

This experiment was carried out in air and at room temperature by LETRY PLG-100 fatigue machine. Whose loading frequency is f=82.1Hz. Experiments were carried out under constant amplitude loading, in which stress ratio R=5 and σ_{max}=10 *KN*.


(a) LETRY PLG-100 High Frequency Fatigue Machine

Fig.11 Prefabricating Initial Crack



(b) Testing Voltages
Fig.11 Prefabricating Initial Crack

After 4.23×10⁶ cycles, the maximum load decreases to 8KN as fatigue crack initiates in the specimen, and then the first step of fatigue experiment is end. The initial crack was shown in Fig12.

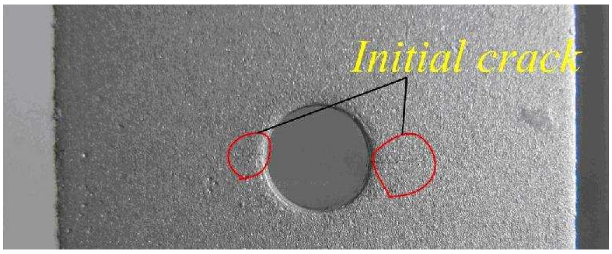


Fig.12 Initial Crack

Here, a set of voltage values corresponding to this initial crack was obtained, which was shown in Table 3.

Table 3 Voltages corresponding to initial cracks

specimen	U_{AB}	U_{AD}	U_{AC}	U_{DC}	U_{BC}	U_{DB}
No.7	0.348	0.322	0.616	0.292	0.267	0.024
No.11	0.419	0.388	0.745	0.356	0.327	0.028
No.13	0.251	0.230	0.533	0.303	0.283	0.020

specimen of No.7: length of initial crack=10.90mm
specimen of No.11: length of initial crack=9.90mm
specimen of No.13: length of initial crack=9.85mm

4.2.1.2 Crack propagation experiment

This crack propagation experiment was carried out in air and at room temperature by MTS810 fatigue machine. Whose loading frequency is f=30Hz. Experiments were carried out under constant amplitude loading, in which stress ratio R=3 and σ_{max}=12 KN.

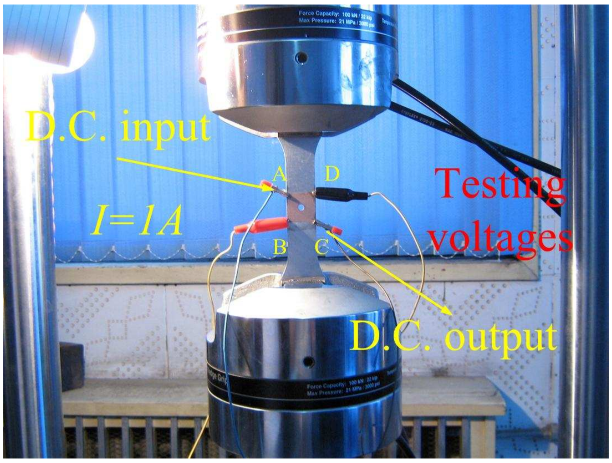


Fig13 MTS810 Low Frequency Fatigue Machine

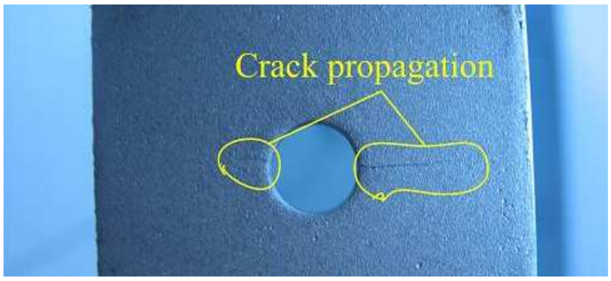


Fig14 Crack Propagation

During this experiment, we took record of the voltages along with the crack propagation. The voltage values and the corresponding crack length are given in Table 4.

Table 4 Voltage values (V) during cracks propagation

specimen of No.7

Crack length (*mm*)	10.98	13.35	14.30	16.10	16.40
U_{AB}	0.351	0.333	0.374	0.345	0.342
U_{AD}	0.315	0.290	0.329	0.293	0.290
U_{AC}	0.590	0.595	0.615	0.580	0.592
U_{DC}	0.275	0.304	0.286	0.288	0.302
U_{BC}	0.238	0.261	0.240	0.236	0.250
U_{DB}	0.034	0.041	0.044	0.050	0.051

specimen of No.11

Crack length (*mm*)	10.25	11.70	15.15
U_{AB}	0.388	0.376	0.313
U_{AD}	0.350	0.336	0.289
U_{AC}	0.658	0.661	0.641
U_{DC}	0.308	0.323	0.354
U_{BC}	0.270	0.283	0.323
U_{DB}	0.036	0.039	0.027

Table 4 Voltage values (V) during cracks propagation

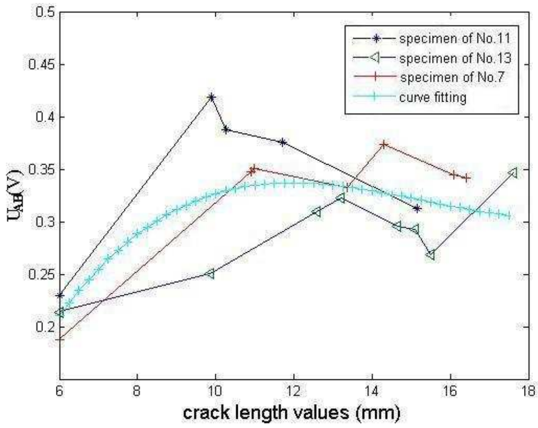
specimen of No.13

Crack length (*mm*)	12.60	13.20	14.65	15.10	15.50	17.60
U_{AB}	0.310	0.323	0.296	0.293	0.269	0.347
U_{AD}	0.281	0.295	0.263	0.261	0.235	0.291
U_{AC}	0.602	0.605	0.576	0.596	0.609	0.668
U_{DC}	0.321	0.310	0.310	0.335	0.365	0.376
U_{BC}	0.292	0.284	0.278	0.304	0.332	0.321
U_{DB}	0.028	0.025	0.031	0.031	0.033	0.053

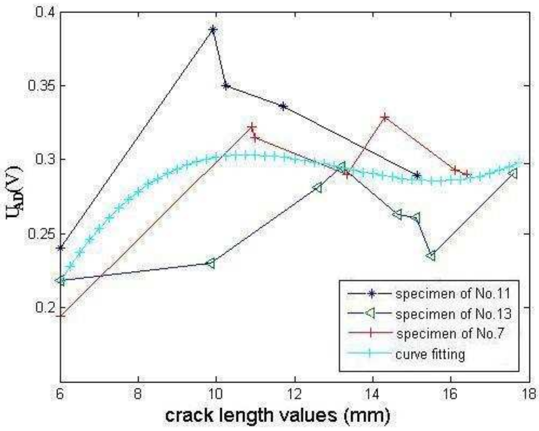
4.2.2 Crack-monitoring results analysis

From the results of the fatigue experiment, we can see that the values of those set of voltage values do change with the fatigue crack propagation.

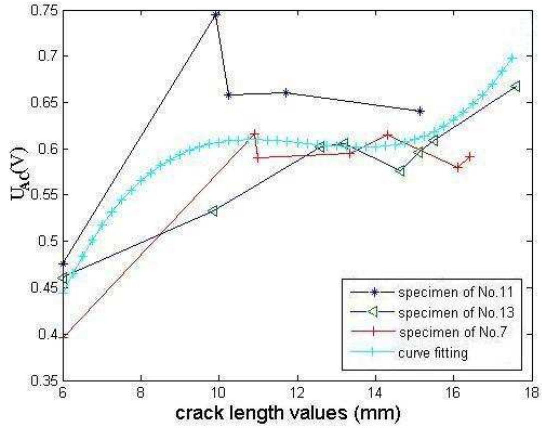
Curves that show the relationship between the voltage values and the crack length are shown in Fig15.



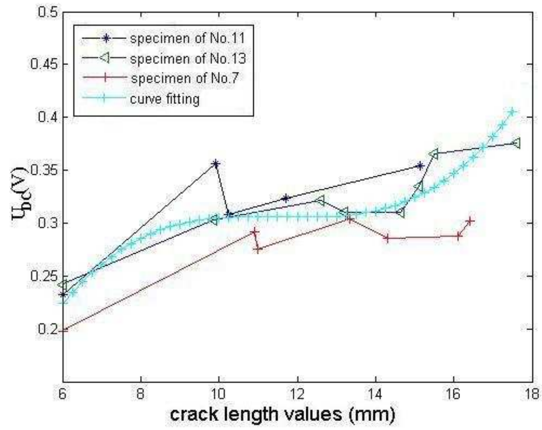
(a) The relationship between U_{AB} and a



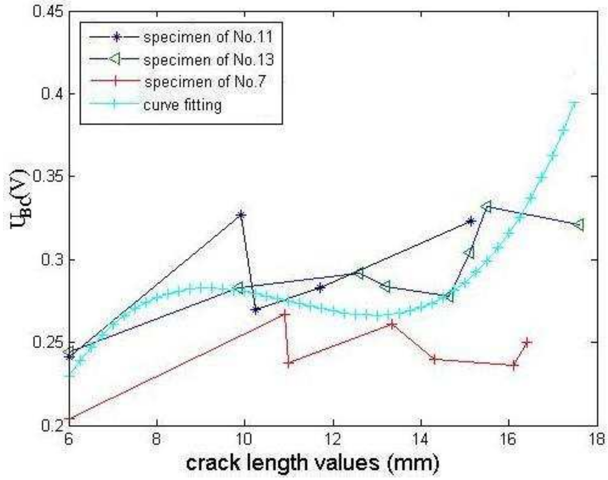
(b) The relationship between U_{AD} and a



(c) The relationship between U_{AC} and a

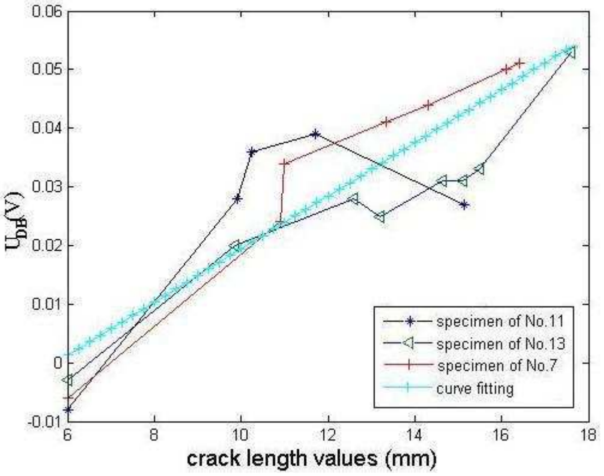


(d) The relationship between U_{DC} and a



(e) The relationship between U_{BC} and a

Fig15 Relationship between voltages and crack length



(f) The relationship between U_{DB} and a

Fig15 Relationship between voltages and crack length

From these curves we can see that during most of the stages of the crack propagation the vector $\bar{U}$ = (U_{AB} U_{AD} U_{AC} U_{DC} U_{BC} U_{DB}) will change correspondingly to the crack propagation. And the vector $\bar{U}$ will change if the crack length values are different. Only in the final stage of the crack propagation, the relationship between ‘ $\bar{U}$ ’ and crack length value “*a*” was anomalous. But the specimen was no longer safe during this stage, so we didn’t take it into consideration.

By fitting the experimental results, we got some approximate formulae as follows:

$$U_{AB}=0.0002a^3-0.0102a^2+0.1482a-0.3604 \quad (1)$$

$$U_{AD}=0.0003a^3-0.0121a^2+0.1553a-0.3434 \quad (2)$$

$$U_{AC}=0.0008a3-0.0288a2+0.3479a-0.7745 \quad (3)$$

$$U_{DC}=0.0005a3-0.0171\ a2+0.1969a-0.4489 \quad (4)$$

$$U_{BC}=0.0006a3-0.0199\ a2+0.2139a-0.4657 \quad (5)$$

$$U_{DB}=0.0045a-0.0259 \quad (6)$$

Considering that:

$$U_{DC}=U_{AC}-U_{AD}, \quad (7)$$

$$U_{BC}=U_{AC}-U_{AB}, \quad (8)$$

$$U_{DB}=U_{AB}-U_{AD}, \quad (9)$$

Finally, the approximate formula can be obtained

$$a=\frac{13U_{AB}-30U_{AD}+8U_{AC}+0.5792}{0.0508}. \quad (10)$$

That is to say at the beginning of the crack propagation we are interested in, a certain crack length only corresponds with a certain $\bar{U}$. So $\bar{U}$ can be seen as a set of characterized parameters to describe a crack, and from the voltages we testing we can get the corresponding crack length. So that it is feasible to monitor the fatigue crack propagation using electric potential method by measuring a certain set of voltage values.

We also can see from the curves that the experimental results of different specimens were not the same. The possible reason for it may include the following factors:

• The electric coats were not produced completely the same;

• The positions of the cracks were different from each other;

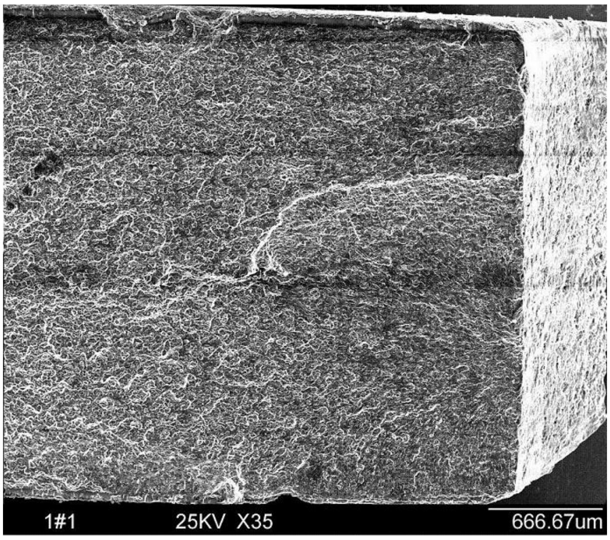
• During the crack propagation, the electric coating may not adhere to the specimen firmly;

• The precision of the devices we used was not enough;

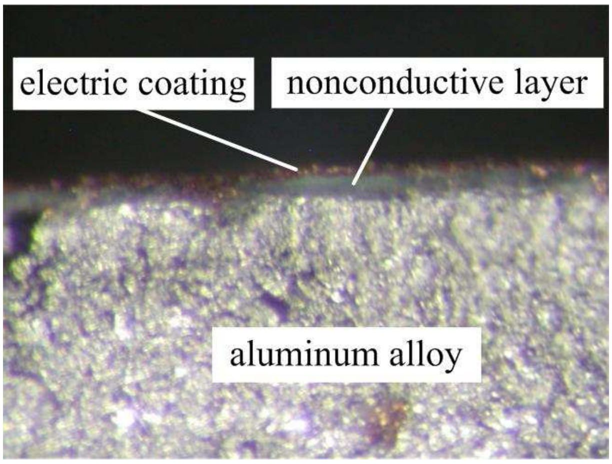
• And there also was some artificial error during these experiments.

4.3 Fractography Analyses of the specimen after fatigue experiment

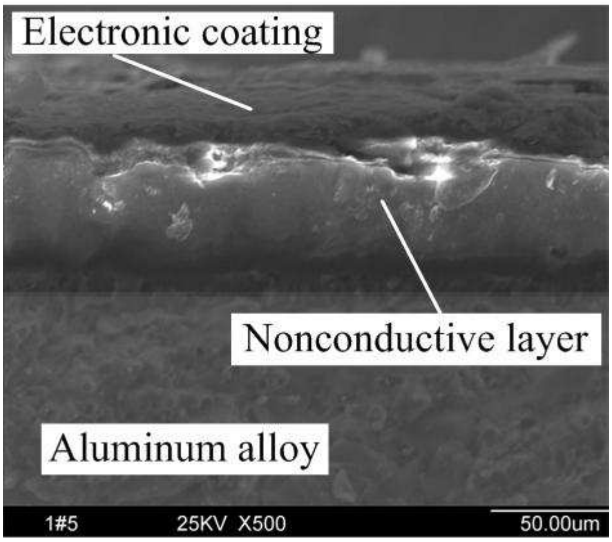
From the section photos shown in Fig.16, we can see it clearly that there are 2 layers on top of the aluminum substrate. One is the nonconductive layer consisting of Al_2O_3 materials in the interconnect layer, and the other is the electric coating on the top.



(a) macro-appearance of the section

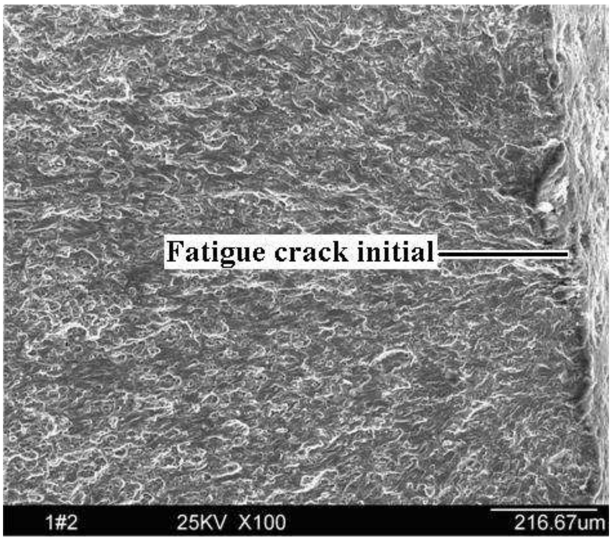


(b) local magnification

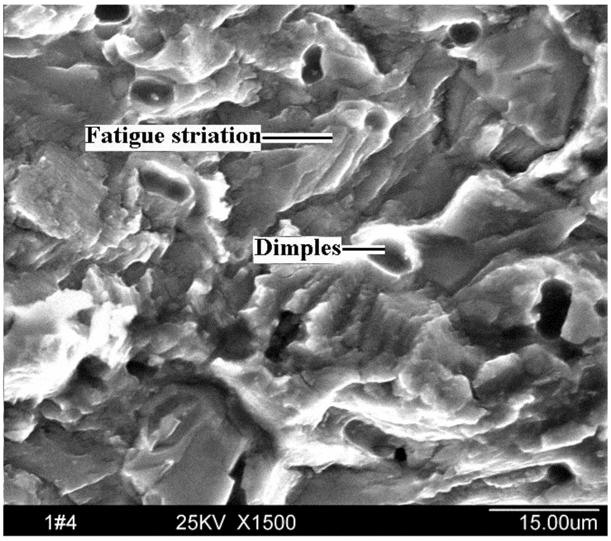


（c）local magnification

Fig.16 section photos obtained by optical microscope-Nikon SMZ800



(a) Fatigue origin



(b) Fatigue Fractography

Fig.17 TEM Fractography Got from TEM.JEM-3010

As shown in Fig.17, the characteristic of fatigue fracture is evident and the fatigue striations can be found easily.

4.4 Conclusions

From the above analyses, some conclusions can be drawn out:

First, it is feasible to get the composite cladding we need on the surface of the aluminum alloy specimen by anodic oxidation technology and hot spraying technology;

Second, the voltage values changed obviously when the initial fatigue crack appears, and they would continually change when the crack propagates;

Third, curves and approximate formulae that show the relationship between crack lengths and the set of voltage values were obtained;

In a word, it is feasible to monitor the fatigue crack initiation and propagation by using electric potential method through measuring a certain set of voltage values.

5 Summary

The feasibility of electric potential method in monitoring cracking is validated through the experiments of monitoring crack in the aluminum foils film.

Researches on monitoring fatigue cracking of typical aircraft structural element--middle-hole plate specimen have been carried out. On these bases, the curves and approximate formulae that show the relationship between crack lengths and a set of voltage values were obtained. These curves and approximate formulae show that a certain crack only corresponds with a set of certain voltage values, and vice versa.

The electric potential method can be used to monitor the fatigue cracking in aircraft structures in-time in the future study. But in this field, lots of research should be done.

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