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Structural Surface Crack Monitoring Method Based on Electrical Potential Technique and Modern Surface Technology

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Abstract: Crack monitoring plays a great role in modern structural health monitoring, however, most of the conventional crack inspections have disadvantages in terms of the accuracy, expense, reliability, durability and level of instrumentation required. Thus, development of a simple and reliable crack inspection technique that allows continuous monitoring has been desired. In this paper, electrical potential technique and modern surface technology are employed together to develop a new structural surface crack monitoring method. A special crack monitoring coating sensor based on electrical potential technique was deposited on the hot spot of the structure by modern surface technology. The sensor consists of three layers: the isolated layer, the sensing layer and the protective layer. The isolated layer is prepared by anodic oxidation technology, the sensing layer is made of ion plated copper, and the protective layer is made of silicone. The thickness of each layer is at micrometer magnitude. The electrical conductivity of the sensor is very stable, and the fatigue performance of the specimen with or without coating sensor is nearly unchanged. The crack monitoring experiment result shows that there are two sudden rises of the coating sensor electrical potential values, corresponding to different stages of the crack initiation and propagation. Since the width of the surface coating sensor is only 0.5 mm, this crack monitoring sensor can detect the propagation of cracks less than 0.5 mm long. The method proposed takes the simplicity of electrical potential technique and can monitor surface crack of nearly all kinds of structures precisely. The results of this paper may form the basis of a new crack monitoring system.

Key words: crack monitoring, electrical potential technique, surface technology, coating sensor, LY12-CZ aluminum alloy

1 Introduction

A serious problem of aged structures is crack propagation induced by fatigue loading or corrosion[1]. Early crack detection is crucial to secure structural integrity because a crack can eventually cause sudden catastrophic failure of structures, which can cause considerable damages both to life and property. Crack detection has been performed by several methods such as penetration dyeing[2], x-ray[3], eddy current[4], ultrasound and acoustic emission (AE) methods[5,6]. However, most of the conventional crack inspections are usually performed during the downtime of the structures[7], so that crack propagation during the interval between periodical inspections can not be found timely and may cause serious damages in the structure. Besides, most of the conventional crack inspections have disadvantages in terms of the accuracy, expense, reliability, durability and level of instrumentation required[8,9]. Thus, the development of a simple and reliable inspection technique that allows continuous monitoring has been desired[10–13].

Among various inspection techniques available, electrical potential technique has been recently paid much attention[14–19]. The advantage of this technique is its simplicity. Moreover, it could provide in situ sensing of the structure. It takes the electrical conductivity of the structure material as a direct damage sensing element[20]. An electric field exists in current carrying material. This electric field will change if a fatigue crack occurs. The crack's location, shape and size may have different impacts on the electric field, shown as different electrical potentials or resistances. As a result, it is possible to get the information about the crack by measuring the potential distribution in the current carrying material before and after crack damage is formed[14,16]. Key questions to be addressed of this technique are the sensitivity and ability of it to locate damage sites within large structures or structures with

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complicated shapes. Besides, it is also difficult to use this technique to detect cracks in nonconductive material structures[17].

In order to overcome the above-mentioned shortcomings, modern surface technology[21] is employed in this study. In most cases, fatigue cracks initiate either at the surface or in close proximity to the surface[22]. And the hotspot, where cracks are easy to occur, can be obtained through theoretical analysis. As a result, imagination can be made that modern surface technology can be employed to prepare a conductive coating sensor with certain shape on the hotspot of the structural surface. When the cracks appear in the structural surface, corresponding cracks will also occur at the surface coating because of accompanying injuries[18]. The occurrence of crack breaks the electrical contact in the structure, which would lead to a change in the electrical potential field around the damage zone. As a result, the crack information can be obtained by analyzing the change of the electrical resistance and/or potential of the conductive surface coating sensor.

This paper mainly studies how to prepare a suitable coating sensor on the hot spots of the structure surface using modern surface technology, and how to monitor the structural surface crack using this coating sensor. The property of the surface coating sensor is stable, and the information of the surface crack of the structure can be obtained by analyzing the change of the resistance (electrical potential) values of the surface coating sensor. The fatigue performance of the specimen with or without surface coating sensor is nearly unchanged.

2 Methodology

2.1 Materials

LY12-CZ aluminum alloy plate specimen is employed as the research object to validate the feasibility of this method. The composition of LY12-CZ aluminum alloy is as follows (wt%): Cu 3.80－4.90%, Mg 1.20－1.80%, Fe≤0.50%, Si ≤0.50%, Ni≤0.10%, Zn≤0.30%, impurity≤0.10% and Al balance. The specimen dimension is shown in Fig. 1.

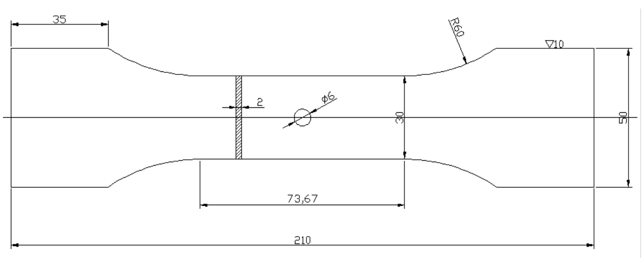

Fig. 1.　Specimen dimension

2.2 Surface coating sensor

As shown in Fig. 2, the surface coating sensor to be made consists of three layers: the isolated layer, the sensing layer and the protective layer. First of all, in order to make sure that only the monitoring area on the specimen surface is conductive, a nonconductive isolated layer is necessary, so that it can space out the substrate and the sensing layer. The sensing layer which is made of conductive materials will be plated on the hot spots of the structural surface by means of modern surface technology, so that the crack propagation in substrate can be reflected by the variation of the electrical conductivity of the sensing layer. The top layer of the surface coating sensor is the protective layer which is used to keep the durability of the coating sensor. The thickness of each layer is only about several micrometers.

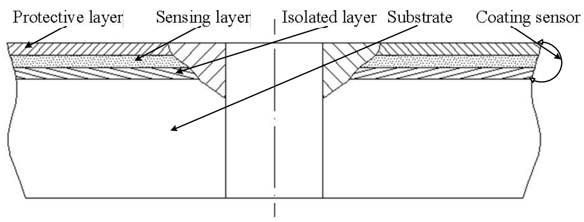

Fig. 2.　Schematic illustration of the surface coating sensor

The shape of the surface coating sensor is designed according to the hot spots of the specimen, which is shown in Fig. 3. The key point of this step is to guarantee the durability of the coating sensor. Another point to be emphasized is that the thickness of the coating sensor should be suitable so that the damage of the coating sensor would have a good agreement with the specimen substrate.

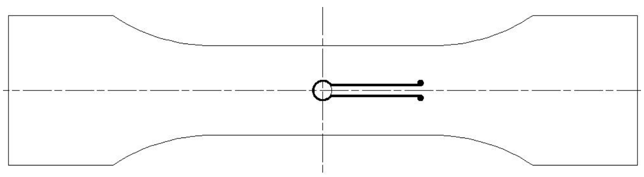

Fig. 3.　Sketch of the surface coating sensor

2.3 Crack monitoring experiment

In order to validate the feasibility of this method in structural crack monitoring, a set of fatigue crack monitoring experiments based on electrical potential technique will be performed. During the experiment, the resistance (electrical potential) values of the surface coating sensor will be recorded along with the crack propagation. And the relationship between the resistance (electrical potential) values of the coating sensor and the crack lengths will be studied. The other task of the experiment is to find out whether the crack monitoring coating sensor is attached to the substrate firmly during the whole fatigue process. All the specimens are not fatigue pre-cracked, so that the whole process of the crack initiation and propagation during the fatigue cycle can be examined.

3 Specimen Preparation

The main work of specimen preparation is to deposit the special crack-monitoring surface coating sensor on the monitoring area (hot spots) of the specimen by means of modern surface technology. There are three layers in the coating sensor, so the process of the specimen preparation mainly includes three steps, making the isolated layer, the sensing layer and the protective layer, respectively.

Since the specimen is made of aluminum alloy LY12-CZ, anodic oxidation technology[21] is applied to prepare the nonconductive isolated layer. The composition of the anodic oxidation solution is as follows (g/L): H_2SO_4 (d=1.84) 40~60, H_3BO_3 5~10, Al^{3+} <20. Table 1 shows the parameters of the anodic oxidation technology. Measuring result shows that the thickness of this layer is about 10 μm.

Table 1. Anodic Oxidation Parameters

Temperature T/℃	Direct current voltage U/V	Current density D/(A•dm^{-2})	Time horizon t/min
25~35	12~20	0.4~2.5	20~40

Ion plating technology[23–25] is an effective surface coating technology widely used nowadays, which can plate continuous, smooth and tight coating of high microhardness and film-matrix strength on structural surface. So this technique is employed in this paper to prepare the sensing layer of the coating sensor. Copper is applied to make the sensing layer in this study.

After polished, the substrates were ultrasonically cleaned for 10 min in acetone. Then, the substrates were mounted on the sample holder. For further cleaning the sample surface to improve the adhesion of the coating to the substrate, argon bombardment cleaning was carried out at the bias voltage of 50 V in a vacuum of 2.4 Pa for approximately 10 min. Finally, Cu coating of 4—8μm was deposited by the HCD process with an IPB30/30 ion plating equipment shown in Fig. 4. Its effective deposition space is Φ 300 mm×300 mm. The thickness allowance of the coatings is ± 0.1 μm in the effective deposition space. The deposition parameters are summarized in Table 2.

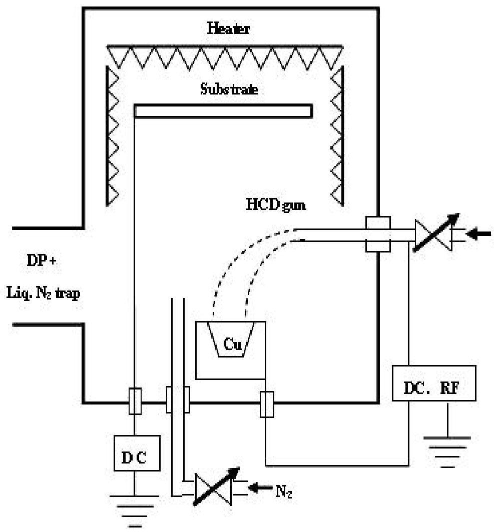

Fig. 4. Sketch of the ion plating technique

Table 2. Deposition parameters

Temperature T/℃	Beam current I/A	Ar pressure P/Pa	Negative bias U/V	Deposition time t/min
<130	40~60	1.0~2.6	200	8~40

Common painting technology is employed here to prepare the protective layer. Silicone is chosen as the protective layer. The thickness of it is about 0.1 mm.

Finally, the specimen with surface coating sensor could be obtained, as shown in Fig. 5. Here, the width of the main part of the coating sensor is 0.5 mm, and the width of the tail part is about 1 mm.

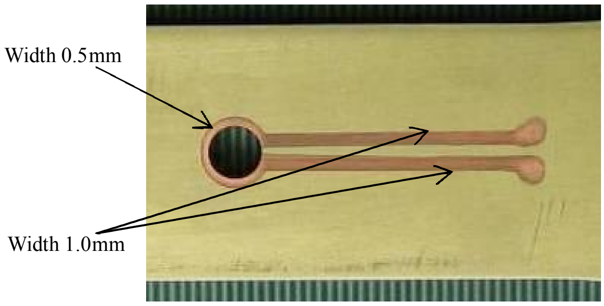

Fig. 5. Specimen with surface coating sensor

Since the electrical conductivity of the surface coating sensor is taken as the damage sensing element, the durability of the coating sensor is really very important. Fig. 6 shows the variation of the resistance of the surface coating sensors versus storage time. The thickness of the sensing layer in specimen No.1 and specimen No. 2 is about 8μm, while the thicknesses of specimen No. 3 and specimen No. 4 are 6 μm and 4 μm, respectively. From Fig. 6, it can be seen that the characteristic of the surface coating sensor is very stable.

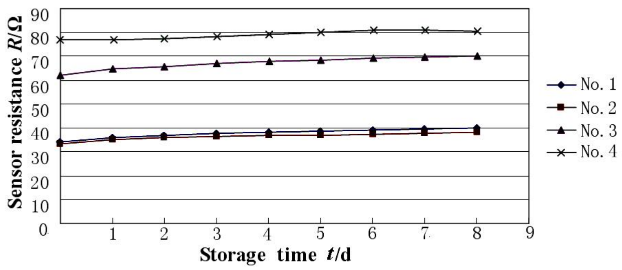

Fig. 6. Variation of the sensors resistance versus storage time

Three groups of specimen are employed to study the effect of the coating sensor to the LY12-CZ substrate fatigue performance. They are LY12-CZ specimen, specimen after anodic oxidized and specimen after ion plating, respectively. These experiments are carried out on an EHF-EA5 material testing machine in air and at room temperature. The experimental parameters are set as follows: R=0.01, f=30 Hz. The load times when the specimens ruptured are documented. Here, if the load times exceed 100×10^5 while the specimen is still undamaged, the experiment will be terminated.

Table 3 shows the fatigue performance research results of that three group specimens. It can be seen that there are no obviously differences between the LY12-CZ specimen and LY12-CZ specimen with surface coating sensor. The experimental results show a good agreement with the results reported by WANG Jiru[26]. That is to say, the surface technology applied in this paper is suitable.

Table 3. Fatigue performance research results

$\sigma_{min} / \sigma_{max}$ (MPa/MPa)	Load times N / 10^5		
	LY12-CZ specimen	Specimen after anodic oxidized	Specimen after ion plating
2 / 200	1.02	1.24	1.10
1.8 / 180	3.10	3.25	3.76
1.6 / 160	2.81	2.94	2.58
1.3 / 130	>100	>100	>100

4 Crack monitoring experiment

After the specimen preparation, crack monitoring experiment based on electrical potential technique could be carried out. Fig. 7 shows the principle of this experiment, in which R represents the resistance of the surface coating sensor. The relationship between the electrical potential values of the coating sensor and the crack lengths are studied. The electrical potential values of the coating sensor are recorded by a XY recorder, the precision of which is 1 mV. And the crack length is obtained by an optical microscope, the precision of which is about 0.1 mm. The constant direct current applied on the coating sensor is 0.5 mA. All the specimens are not fatigue pre-cracked, so that the whole process of the crack initiation and propagation during the fatigue cycle can be examined.

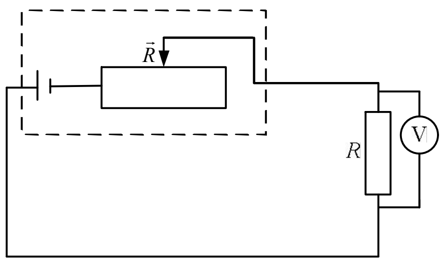

Fig. 7. Circuit diagram of crack monitoring experiment

4.1 Experimental procedures

The crack monitoring experiment is carried out on an EHF-EA5 material testing machine in air and at room temperature, as shown in Fig. 8. The load error of the EHF-EA5 material testing machine is less than 1%.

Fig. 8. Crack monitoring experiment

Constant amplitude loading was applied in this experiment. In order to save time, at the early stage of the experiment when there was no crack occurred, the experimental parameters were set as follows: loading frequency $f = 5Hz$, stress ratio $R = 0.03$, maximum stress $\sigma_{max} = 80MPa$. And when crack was observed during the experiment, the experimental parameters were changed as follows: loading frequency $f = 1Hz$, stress ratio $R = 0.03$, maximum stress $\sigma_{max} = 60MPa$, so that a good observation of the crack propagation could be obtained.

During the experiment, the resistance (electrical potential) values of the surface coating sensor were recorded along with the crack propagation.

4.2 Results and analysis

The surface coating sensor after the crack monitoring experiment is shown in Fig. 9, from which it can be seen that there no delamination or desquamation exists in the coating sensor. This means that during the whole process of the crack initiation and propagation, the surface coating sensor is integrated with the LY12-CZ substrate firmly, and the wear resistance of the coating sensor is very well.

Fig. 9. Surface coating sensor after crack monitoring experiment

The variation of the electrical potential values of the surface coating sensor versus the experiment time is shown in Fig.10. It can be seen that the electrical potential values of the surface coating sensor does change regularly along with the structural crack propagation. There are two sudden rises of the electrical potential values of the surface coating sensor during the crack monitoring experiment. The first one appears between point A and point B, and the other appears between point C and point D. Visible fatigue crack was found after point C.

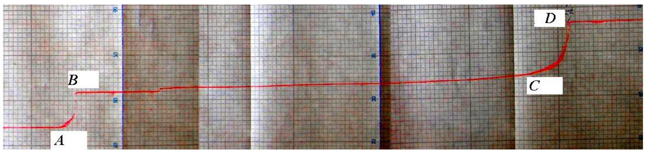

Fig. 10. Variation of the resistance (electrical potential) values of the surface coating sensor versus experiment time

In the early part of this curve before point *A* the electrical potential value is nearly a constant, which presents that there is no fatigue damage on the specimen. The first sudden rise of the voltage values between point *A* and point *B* must be caused by the plastic deformation of the structure, although there are no cracks appear. And the other sudden rise between point *C* and point *D* shows the variation of the sensor resistance values during the crack initiation and propagation, which could be observed through the optical microscope. The last part of this curve shows the situation after the crack grew across the surface coating sensor.

Since the width of the surface coating sensor is only 0.5 mm, this crack monitoring sensor can detect the propagation of cracks less than 0.5 mm long. As a result, it can be concluded that the information of the surface crack of the specimen could be obtained from the resistance (electrical potential) values recorded during the experiment, which prove that it is feasible to monitor the fatigue crack of the specimen by the method presented in this paper.

5 Conclusions

(1) A composite crack monitoring coating sensor consisting of three layers can be prepared on the hot spots of the LY12-CZ Aluminum alloy plate specimen using modern surface technology.

(2) The electrical conductivity of the sensor is very stable, and the fatigue performance of the LY12-CZ specimen with or without coating sensor is nearly unchanged.

(3) There are two sudden rises of the coating sensor electrical potential values, corresponding to different stages of the crack initiation and propagation.

(4) This crack monitoring sensor can detect the propagation of cracks less than 0.5 mm long.

References

[1] PITT S, JONES R. Multiple-site and widespread fatigue damage in aging aircraft [J]. *Engineering Failure Analysis*, 1997, 4(4): 237−257.

[2] GLATG J W. Detecting micro defects with gas penetrants [J]. *Metal Progress*, 1985, 127(2): 18−22.

[3] NIEMANN W, ZAHORODNY S. Status and future aspects of X-Ray backscatter imaging [J], *Review of progress in Quantitative Nondestructive Evaluation*, 1997, 17A: 379−385.

[4] NEIL G, VLADIMIR Z, ANDREW W, et al. Eddy current sensor networks for aircraft fatigue monitoring [J]. *Materials Evaluation*, 2003, 61(7): 1–13.

[5] ROKHLIN S I, KIM J Y. In situ ultrasonic monitoring of surface fatigue crack initiation and growth from surface cavity [J]. *International Journal of Fatigue*, 2003, 25(1): 41–49.

[6] SCHUBERT F. Basic principles of acoustic emission tomography [J]. *Journal of Acoustic Emission*, 2004, 22: 147−158.

[7] HIROSHI T, JUNG R L and GUAN Y. Fatigue crack propagation monitoring of stainless steel using fiber bragg grating ultrasound sensors [J]. *Smart Materials and Structures*, 2006, 15: 1 429–1 437.

[8] GUO Wanlin, SHAO Renping, FENG Qian. A review and prospect of damage detection in structures [J]. *Journal of Vibration, Measurement & Diagnosis*, 2003, 23(2): 79−85.

[9] OU Meigui, LIANG Yilong, XIANG Qizhi. Assessment of monitoring methods for small fatigue cracks [J]. *Guizhou Science*, 2002, 21(3): 20−24.

[10] XIONG Haibei, LI Zhiqiang. State of the Art of Structural Health Monitoring [J]. *Structural Engineers*, 2006, 22(5): 86−90.

[11] YANG Zhichun, YU Zhefeng. Progress of damage detection for structural health monitoring [J]. *Advances in Mechanics*, 2004, 34(2): 215−223.

[12] HU Zili, XIONG Ke, YANG Hong. Damage evaluation methods based on smart materials and structures [J]. *Acta Aeronautica et Astronautica Sinica*, 2002, 23 (1): 2−5.

[13] GAMA A L. MORIKAWA S R K. Monitoring fatigue crack growth in compact tension specimens using piezoelectric sensors [J]. *Experimental Mechanics*, 2008, 48(2): 247–252.

[14] ANGELIDIS N, KHEMIRI N and IRVING P E. Experimental and finite element study of the electrical potential technique for damage detection in CFRP laminates [J]. *Smart Materials and Structures,* 2005, 14: 147–154.

[15] TODOROKI A and TANAKA Y. Delamination identification of cross-ply graphite/epoxy composite beams using electric resistance change method [J]. *Compos. Sci. Technol.*, 2002, 62(6): 29–39.

[16] WANG S, SHUI X, FU X and CHUNG D D L. Fatigue damage in carbon-fibre composites observed by electrical resistance measurement [J]. *Mater. Sci*. 1998, 33(38): 75–84.

[17] CUI Ronghong. Application of Electrical potential technique to Monitoring Surface Fatigue Cracks of Structures [D]. *Master's degree Dissertation. Air Force engineering University*, China. 2007.

[18] HE Yuting, LI Hongpeng, CUI Ronghong, et al. Monitoring Crack Growth by means of Electrical Potential in Surface Coating of Aluminium Alloy Structure Specimen [C]. *Proceedings of international conference on health monitoring of structure, material and environment*. Nanjing, China, October 16−18, 2007: 1 245−1 249.

[19] LIU Mabao, GAO Qian, HU Feng, et al. Flaw-Detected Coating and Application [C]. *Proceedings of international conference on health monitoring of structure, material and environment*. Nanjing, China, October 16−18, 2007: 1 189−1 192.

[20] SCHUELER R, JOSHI S. P. and SCHULTE K. Damage detection in CFRP by electrical conductivity mapping Compos [J]. *Sci. Technol.* 2001, 61(9): 21−30.

[21] DONG Y. *Modern surface engineering and technology* [M]. China Machine Press, 2000.

[22] WU Fu Min. *Fatigue strength of structures* [M]. Xi'an: Northwestern Polytechnical University Press, 1985.

[23] LIU Gaojie, DENG Chunzhi. The technology research of HCD hollow negative pole ion plating [J]. *China Molybdenum Industry*. 1997, 31(4): 46−48.

[24] WANG Zengfu, CHEN Buliang, FAN Bing, et al. New development of ion coatng equipment in multi-layer film [J]. *Vacuum*, 2002, 39(3):10−12.

[25] JIANG Xuefeng, LIU Qingcai, WANG Haibo. Technology and application of multi-arc ion plating [J]. *Journal of Chongqing University (Natural Science Edition)*, 2006, 29(10): 55−57.

[26] WANG Jiru, CAI Jianping, XIONG Yu, et al. Research progress of non-chromate coatings for aircraft in the world [J]. *Modern Paint and Finishing*. 2005, 11(2): 39−41.

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