Introduction of Some Researches on Electromagnetic NDT

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Abstract: In this paper, some research activities performed by authors on the Electromagnetic Nondestructive Evaluation (ENDE) for materials and structures of nuclear and other industries are introduced. The major contents includes, theoretical and experimental studies on NDT of ultra-light material and structures, NDT methods for Thermal Barrier Coating (TBC) inspection, improvement on quantitative NDT method of Stress Corrosion Crack (SCC), new inspection method for material degradation etc. Research methods, typical results in addition with objectives are presented.

Keywords: ENDE, Review, Ultra-light Material, Thermal Barrier Coating, SCC, Deep Crack

1. Introduction

In this article, recent research works related to Electromagnetic Nondestructive Evaluation (ENDE) that are conducted in NDT Lab of Xi'an Jiaotong University partly in cooperation with Tohuku University are briefly introduced. Eddy Current Testing (ECT) techniques, Direct Current Potential (DCPD), Electromagnetic Acoustic Testing (EMAT) and some new NDT techniques are upgraded and proposed for applications to the inspection of key structural components of nuclear power plant and some other structures of new materials such as ultra-light material and Thermal Barrier Coating (TBC). The backgrounds, technical approaches, and some typical results are described.

At first, developments on the NDT method for two typical ultra-light materials – metallic foam and metallic lattice sandwich plate are introduced. Proposal and validation of NDT methods for inspection of delamination and coating thickness reduction of TBC are presented then with validations based on numerical simulations. Third, upgrading of inversion techniques of Stress Corrosion Cracks (SCC) to improve the sizing precision is described. Finally, a strategy for distinguishing SCC and fatigue crack, and some researches on the NDT of mechanical damage in austenitic stainless steel based on natural magnetic field are given.

2. Inspection of Ultra-light Material

Ultra-light material is novel and multifunctional material which has advantages of high strength, high stiffness and low density, and widely applied in many industries, such as aerospace engineering, transportation etc. There are two typical ultra-light materials, one is the foam material and the other is the material of lattice structure. Up to now, there are still no satisfactory NDT techniques being established yet for the Pre-Service (PSI) and In-Service Inspection (ISI) of the ultra-light material and structure. Considering the features of the ENDE, inspection method of metallic foam and metallic lattice sandwich plates are studied in our group, and a strategy based on the ECT and the DCPD method has been developed. The research works related to this topic are as follows:

(1) Inspection of metallic foam [1]

Metallic Foam (MF) possesses features including super lightness and high mechanical energy absorption. The fabrication method of MF is mainly a frothing technique. There may occurs large bubble flaws in MF during the process of frothing manufacturing, i.e., some vicinal small bubbles may unite to a large cavity flaw which will greatly affect the performance of MF. Therefore, Pre-Service Inspection (PSI) with NDT approach for the inner bubble flaws is important before the material is used.

Considering the features of the metallic foam, DCPD method is selected for the inspection of the bubble flaw. To evaluate the performance of the method, efficient numerical simulation methods are developed based on 3D FEM and a pre-calculated database of scalar potential. Numerical simulation shows that there is a good possibility of DCPD method to detect an inner bubble flaw if it is not very

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small. On the other hand, DCPD experiments are performed to investigate detectability for bubble flaws in simulated aluminium metal foam test-pieces and practical Al metallic foam. The experimental results proved the prediction of the numerical simulation, and show that DCPD can be a good candidate for the NDT of metallic foam. At the same time, the measurement results also verified the validity of the new fast numerical method and related code. The final conclusion of this study is that the DCPD method can detect inner bubble flaws of size bigger than 30% of the thickness of the metallic foam test-piece.

(2) Inspection of metallic lattice sandwich plate

Lattice sandwich metallic plate (LSMP) is a newly developed ultra-light material, which plays an important role in many industries for its features of high strength and low density. Usually, LSMP is made of two surface plates and an inner truss layer that are bonded together by a welding technique. The mechanical behaviors of LSMP greatly depend on the quality of welding joints. Defects in welding joints will cause strength reduction in LSMP and consequent structure failure. Unfortunately, there is also still no satisfactory NDT method being established for the inspection of welding defects in LSMP [2, 3].

As the surface layer is not thick, ECT is possible to be applied to detect the cracks initiated in the surface plates. However, as cracks usually occurs in the welding joint zone and in the opposite side of the inspection surface, special techniques are necessary to enhance S/N ratio. In addition, because welding defect such as debonding is often parallel to surface plate, ECT is not efficient for welding defects. On the other hand, DCPD is widely used to detect varied kinds of cracks as the path of injected current of DCPD is easier to be controlled. In principle, the welding quality of LSMP may also affect the impedance property of welding joints, and further the potential drop distribution. Therefore, there is a possibility to evaluate welding quality of LSMP based on the potential drop signals. Based on these considerations, a hybrid strategy is proposed for NDT of LSMP, i.e, to detect cracks in welding zone with ECT and welding defect with DCPD. The validity of this strategy is investigated in both numerical and experimental ways.

The feasibility of ECT for both detection of cracks at the welding zones in the surface plate and sizing of cracks using the mixed crack and noise signals is studied. Through numerical simulations, it is found that the defects in the welding zone cause ECT signals of significant different phase property with those caused by welding bead. Therefore, the Multiple Frequency signal processing Algorithm (MFA) is applicable to process the mixed ECT signals in order to improve the S/N ratio, which enables the recognition of crack indication from the mixed ECT signals detected at a welding joint. Through measuring and processing signals due to artificial crack in weld joint zones, the validity of ECT for detecting cracks in LSMP is verified. In addition, a modified MFA, which uses signals of more than 3 frequencies, is proposed and is proved capable to increase S/N ratio further. On the other hand, by introducing a multi-frequency inversion algorithm, the profile reconstruction of a crack in the welding zone is successfully realized for both simulated ECT signals and measured ones. It is demonstrated that ECT is a suitable quantitative NDE technique for cracks in the LSMP.

For validating the DCPD method for welding defects, numerical code and experimental systems are established respectively. Through numerical analysis and experimental validation, it is proved that DCPD method can detect debonding defect efficiently. It is also found that, the size of the welding defect is also possibly to be determined by using a calibration strategy. Together with the ECT technique, the NDT problem of LSMP can be solved efficiently.

3. NDT Method for TBC Inspection

Thermal Barrier Coating is a key structure to reduce temperature in blade of gas turbine. The quality of TBC system is very important to guarantee the integrity of the blade and consequently the safety of the gas turbine. The delamination is the major concern of the TBC system. On the other hand, the reduction of the thickness of the top coating of TBC, which is a key parameter of TBC for thermal barrier function, is also necessary to be monitored. To detect the delamination in a TBC system, an EMAT based method is proposed and its validity is evaluated through numerical analysis. For the thickness evaluation and tiny crack inspection, a multiple high frequency ECT approach is applied and its efficiency is studied both numerically and experimentally [4].

At first, a new transducer based on EMAT principle is proposed to detect the delamination in TBC. To evaluate its feasibility, a numerical code based on FEM and reduced A method is developed and applied to the simulation of TBC inspection. The influence of electro-magneto-mechanical coupling due to speed effect on the EMAT signals is studied. To improve the neck point of FEM for UT simulation, i.e., the great computation burden, a new explicit integration algorithm of time domain is introduced, which can reduce the data operand and memory capacitance significantly. Through numerical analysis, it is found that even for a delamination less than 1 mm, the new transducer can give a clear difference between the flawed and unflawed signals.

To detect the thickness of top coating, a multiple high frequency ECT approach is introduced to predict the coating thickness of a multiple layer TBC structure. As the coating thickness is very small and the material property is also possibly changed during a long term of service, they have to be reconstructed from the ECT signals simultaneously. On the other hand, the inspection of the crack propagated into the base material of the turbine blade can be realized by high frequency ECT. Even for small cracks at the edge of blade, the researches show that ECT of 1 MHz is efficient to detect them.

4. Enhancement of Sizing Technique of SCC

SCC is inclined to grow with the running of NPP. In order to meet the demands on both the safety and economic interests, sizing of SCC is an important task once it is detected in a key structural component of NPP. As a supplement of UT, the ECT technique has been applied to the reconstruction of several kinds of natural cracks including some SCC. For a deeper SCC, however, the reconstruction accuracy is still not satisfactory even using the conductive crack model, as the conductivity and shape of SCC may significantly change at different crack depth [5, 6, 7].

In our studies, schemes to improve the ECT inversion accuracy for a deep SCC and a long SCC is proposed, which reconstruct crack profile at different depth with signals of different excitation frequencies and liftoffs, and a multiple segments strategy is applied to solve the problem of long crack. Several cracks are reconstructed to demonstrate the efficiency of the proposed strategies. For a long SCC, the multiple segment strategy can reconstruct cracks with very complicated crack shape in length direction by using signals scanned in perpendicular to the crack length. For the deep crack, because of the application of multiple frequency and liftoff, the less prediction problem of the conventional ECT inversion scheme is improved.

As just mentioned, a high precision sizing of SCC based on ECT signals is difficult without knowing the distribution of conductivity in crack region. However, there is little knowledge up to now about the features of the conductive distribution in a SCC region. Aiming at investigating distribution of conductivity around a SCC, two schemes based on the ECT signals and signals of DC potential drop are proposed, and the 3D conductivity distribution is measured by using these methods layer by layer. The major works and results of our experiments are as follows:

(1) The conductivities of a SCC at different layers are obtained from measured ECT signals. After measuring ECT signals with two ECT systems respectively for selected frequencies, the signals are calibrated based on signals of a standard crack and the conductivities of each crack layer are obtained from the calibrated signal using the standard curve. As the major results of this part, the relative conductivities of different crack layers are 4%~8%, 6%~9%, 9%~15%, 13%~19% respectively for 4 mm depth SCC.

(2) The conductivity of each SCC layer is also predicted through signals of four probe DC potential measurement. The measured potential signals are compared with those simulated with ANSOFT software in order to obtain the conductivity distribution. The results are about 11%, 12%, 12%, and 22% respectively for the four crack layers. In addition, the distribution of conductivity is also measured by using four probe method based on another set of SCC samples that were sliced along the length direction. The results demonstrated that the conductivity of SCC at center region is smaller than that at the edge region.

Comparing the results getting with the two methods, it is found that the two sets of results agree with each other qualitatively, which demonstrated the methods for crack conductivity prediction are efficient even for a SCC, and the conductivity of a SCC may ranges most possibly from 5% to 20%.

5. ECT Techniques for Sizing of Deep Crack

Recently, ECT is also considered to be applied to the sizing of crack depth. Because of skin-effect, however, ECT has a particular limitation that it is difficult to recognize the depth of deep cracks in a thick plate because the signals amplitudes will be saturated if the crack depth is too large. To improve the sizing capability of ECT, authors have proposed a unique excitation unit of split segments for ECT probe. In recent works, authors have proposed a modified strategy for the suppression procedure, where the amplitude of signals at a selected small region is minimized together with the phase angle by adjusting both the amplitude and phase of the exciting current. In addition, to improve the sizing capacity of ECT further, the feasibility of a transmission type ECT probe is also evaluated [7].

The major works and results are as follows:

1) The key idea of the new approach for deeper eddy current penetration is that, not only the amplitude, but also the phase of the excitation current in the two pairs (four) of exciting coils are adjusted to suppress the eddy currents on the surface of the inspection target. In addition, the transformation factors are determined to reduce eddy current at a selected region but not that at a point. Numerical simulations are performed to investigate the validity of the new methods and the results reveal that the modified way can give some improvement of sizing capability for deep cracks.

2) In order to enhance the sizing capability of ECT for a deep crack, a split TR probe is also proposed and evaluated. In this case, a rectangular exciting coil is put at the crack opening side of the specimen and the pickup coil is set at the other side. A deep crack will give relatively larger pickup signal as

the crack tip is near by the pickup coil. Numerical and experimental results reveal that the split TR probe is promising for the sizing of deep cracks though the signals can be small. A special merit of this kind of probe is that the phase angle of the peak signal is almost linearly proportional to the crack depth, which makes the sizing procedure much easier.

6. Crack Distinction and Damage Inspection

(1) Distinguish method of crack type [8]

Recently, a novel nondestructive strategy is proposed for distinguishing SCC and a Fatigue Crack (FC) based on ECT signals by authors. The strategy consists of measurement procedures with a special ECT probe and crack type judgment scheme based on an index parameter that is defined as the amplitude ratio of the measured signals. An ECT probe, which can induce eddy current flowing mainly in a selected direction, is proposed and applied to detect crack signals by scanning along the crack with different probe orientation. As the ratio of the amplitudes of signals detected for parallel and perpendicular probe orientation is sensitive to the microstructure of the crack, i.e., the parameter is much bigger for a fatigue crack than that of an SCC, whether a crack is an SCC or an FC can be recognized nondestructively by comparing the index parameter with a threshold value. In order to verify the validity of the proposed strategy, many artificial SCC and FC test-pieces are fabricated and ECT inspections were performed. Numerical simulations are also conducted to investigate the physical principles of the new methodology. From both the numerical and experimental results, it is demonstrated that the strategy is very promising for the distinction of artificial SCC and FC. There is also good possibility that this method can be applied to natural cracks.

(2) Damage inspection using natural magnetic field

Austenitic stainless steel has been extensively used in NPP. The NDT of its mechanical damage at pre-crack state is very important for the further safety assessment of a NPP. Aiming at to develop a new NDT method for inspecting mechanical damage before the initiation of macro cracks, the correlation between the natural magnetization and the mechanical damage is experimentally investigated for a typical austenitic stainless steel - SUS304. In the experiments, simple tensile loads are applied to lateral notch specimens to generate states of different plastic damages, and the corresponding natural magnetic field and residual strain distribution were measured after each loading cycle. The surface plastic deformation distribution is measured by using an instrument of optical image analysis method. The distribution of natural magnetization is analyzed based on the measured magnetic field signals and dependence of the magnetization on the mechanical damage was discussed. The experimental results reveal that there is a good possibility to detect mechanical damages by measuring the natural magnetic field [9].

7. Conclusions

In this article, some recent research works on Electromagnetic Nondestructive Evaluation conducted in NDT Lab of Xi'an Jiaotong University partly in cooperation with Tohuku University are briefly introduced.

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