Quantitative Non-destructive Testing of Metallic Foam Based on Direct Current Potential Drop Method

Jing Zhang[1], Shejuan Xie[1,2] and Zhenmao Chen[1]*
[1]*MOE Key Laboratory for Strength and Vibration, Xi'an Jiaotong University, Xi'an, 710049, China*
[2]*Institute of Fluid Science, Tohoku University, Katahira 2-1-1, Aoba-ku, Sendai, 980-8577, Japan*
** Corresponding author, chenzm@mail.xjtu.edu.cn*

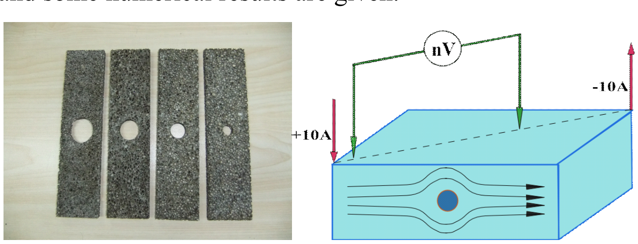
Abstract — To detect cavity defects in a metallic foam and to predict its size, a quantitative NDT method based on the direct current potential drop (DCPD) technique was proposed and evaluated in this study. At first, an efficient forward analysis method was introduced to simulate DCPD signals. A DCPD experimental system was set up and plate specimens of aluminum metal foam with defects of different sizes were fabricated then to measure signals for defect reconstruction. Third, an inverse analysis scheme in model based optimization category is implemented for sizing the cavity defects in metal foam. Through inversions of both simulated and measured DCPD signals, the validity of both the forward and the inverse analysis scheme was verified for the quantitative DCPD inspection of the metallic foam.

Key Words: Metallic foam, DCPD, Inversion, Cavity defect

I. INTRODUCTION

Metallic Foam (MF) of high porosity as shown in Fig.1, is a new kind of material with many good features, such as super-light, high specific strength, high mechanical energy absorption etc., and was applied in many industrial areas. The quality of the MF is a key for realizing its advanced functions that requests no cavity defect exceeding permitted size [1]. Pre-Service Inspection (PSI) in a nondestructive way is important to guarantee the quality of the MF. Up to now, there is still no satisfactory method for its quantitative NDT. The efficiency of the Direct Current Potential Drop (DCPD) method has been investigated for applications to the detection of defect in MF by authors [2]. In this paper, a sizing scheme based on DCPD signals and a deterministic inverse analysis method was proposed and validated for the quantitative NDT of MF.

In the first part of this paper, the fast simulation method for DCPD problem of MF is presented. The experimental set up and validation of the forward solver are presented then. In the third part, algorithm for defect reconstruction and some numerical results are given.



(a) Samples of MF (b) Numerical model of DCPD

Fig.1 Test-pieces of metallic foam and numerical model of DCPD

II. FAST NUMERICAL SIMULATION OF DCPD SIGNALS

The basic formula of the fast scheme for forward analysis of DCPD inspection of MF, which can be derived by subtracting the governing equations of the steady current problems with and without defect present [2], is as follows,

$$\nabla\cdot\sigma_0(\mathrm{r})\nabla\varphi_{\mathrm{f}}=\nabla\cdot(\sigma_0(\mathrm{r})-\sigma(\mathrm{r}))\nabla(\varphi_0+\varphi_{\mathrm{f}}), \qquad (1)$$

where $\varphi_f=\varphi-\varphi_0$ is the potential perturbation due to the flaw, with φ and φ_0 the scalar potentials in the conductor with and without cavity flaw, respectively, and $\sigma(\mathbf{r})$, $\sigma_0(\mathbf{r})$ are the conductivity distribution functions for the conductor with defect present and absent.

After FEM discretization [3],[4], the following system of linear equations can be obtained,

$$\begin{Bmatrix}\varphi_{1f}\\ \varphi_{2f}\\ \varphi_{3f}\end{Bmatrix}=-\begin{bmatrix}H_{11} & H_{12} & H_{13}\\ H_{21} & H_{22} & H_{23}\\ H_{31} & H_{32} & H_{33}\end{bmatrix}\begin{bmatrix}o & o & o\\ o & K_{22} & o\\ o & o & o\end{bmatrix}\begin{Bmatrix}\varphi_{10}+\varphi_{1f}\\ \varphi_{20}+\varphi_{2f}\\ \varphi_{30}+\varphi_{3f}\end{Bmatrix}, \qquad (2)$$

as the right hand of Eq.(1) vanishes outside of the defect. In Eq.(2) subscripts *1, 2* and *3* represent that a corresponding component belongs to the measuring surface, cavity flaw and the other part, respectively, $[H]$ is the inverse matrix of the unflawed global coefficient matrix and $[K_{22}]$ is the coefficient sub-matrix related to the flaw region. From Eq. (2), the following equations can be obtained,

$$\{\varphi_{1f}\}=-[H_{12}K_{22}]\{\varphi_{20}+\varphi_{2f}\}. \qquad (3)$$

From Eq.(3), potential perturbation at the nodes of the measuring surface φ_{1f} can be solved, and the full potential values at these nodes, φ_1, can be obtained consequently. As $[H]$ and $\{\varphi_0\}$ are independent of the flaw geometry, they can be pre-calculated using a full FEM code and stored as databases. Thus, large reduction in computer resources can be realized for simulating DCPD signals due to defects of different size because the number of the nodes in the flaw region and the measuring surface is much smaller than that of the whole analysis region.

III. DCPD INSPECTION EXPERIMENTS

To validate the fast simulation code for DCPD signal simulation, and to obtain the DCPD signals for defect reconstruction, DCPD experiments are performed for Test-Pieces (TP) of aluminum MF with artificial cavity defects of different size. The DCPD experimental platform as shown in Fig.2 was set up and four specimens as shown in Fig.1(a) were fabricated, in which defects of different sizes are fabricated in the middle of the TPs.

In the DCPD testing system, a DC source was used to load direct current up to 40 A to the specimens, and a nano-volt meter and a PC were used to measure the potential values at the top surface of the specimens through an A/D board. The movement of the probes was controlled by using a PC automatically. The numerical and experimental results of TP No.1 were compared in Fig.3. Results of TP No.2 to No.4 were similar. These results proved the efficiency of the DCPD method for the NDT of MF and also the validity of the fast simulator.

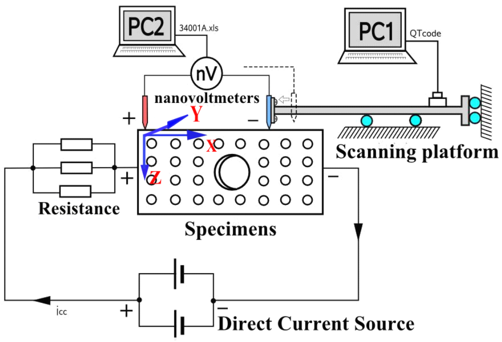


Fig. 2 DCPD testing system

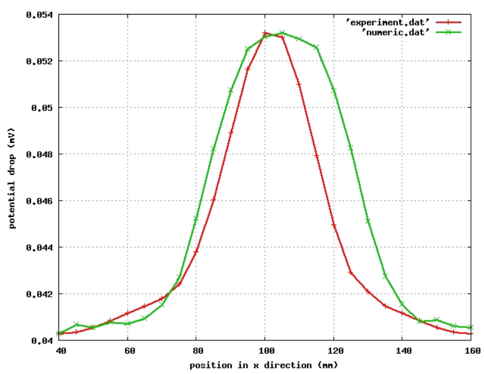


Fig.3 Comparison of numerical and experiment results (TP No.1)

IV. Inversion Scheme for MF Defect Sizing

An inverse analysis method based on deterministic optimization algorithm is adopted to reconstruct the profile of the cavity defect from the measured DCPD signals. The basic procedure of the inversion is as follows:

At first, we define the objective function $\varepsilon(\mathbf{b})$ as,

$$\varepsilon(\mathbf{b}) = \sum_{m=1}^{M} \left\| u_m(\mathbf{b}) - u_m^{obs} \right\|^2 \tag{4}$$

where, $\mathbf{b}$ is the vector of the defect profile parameters, $u_m(\mathbf{b})$ and u_m^{obs} are potential values at the m-th sampling point of the measuring surface, M is the total number of data points. For TPs shown in Fig.1, only the starting and the ending element number b_1, b_2 and b_3, b_4 in the x and z direction respectively are taken as the defect parameters, i.e., $\mathbf{b}=\{b_1, b_2, b_3, b_4\}^t$, as the defects are through holes in y direction.

With gradient based optimization method, vector $\mathbf{b}$ can be solved by minimizing the objective function through the following iteration procedure,

$$\mathbf{b}_k = \mathbf{b}_{k-1} + \lambda_k \mathbf{P}_k \tag{5}$$

where $\mathbf{P}_k$ is the updating direction of k-th iteration, which is chosen as the direction of the gradient vector in case of the steepest descent algorithm. λ_k is a step size parameter selected as the value reducing $\varepsilon(\mathbf{b})$ most efficiently [5].

Based on the above algorithm, a code was developed for the reconstruction of the cavity defects in order to reconstruct the defect parameters (position and size) properly from the measured DCPD signals.

The inversion method and the corresponding numerical code were validated by reconstructing 2D cavity defects from simulated DCPD signals at first. Figure 4 shows a comparison of true signals with the signals due to the reconstructed defect and the selected initial value. In this case, the initial parameters $\mathbf{b}^{init}$ was selected as {2, 10, 13, 25} and the true defect parameter was $\mathbf{b}^{obj}$ ={3, 8, 18, 23}. Through 30 steps of iterations, the reconstructed defect parameters converged to {3, 9, 18, 23}, which is in a good agreement with true values. The algorithm is also verified applicable for other conditions by comparing inversion results of different defects and initial parameters.

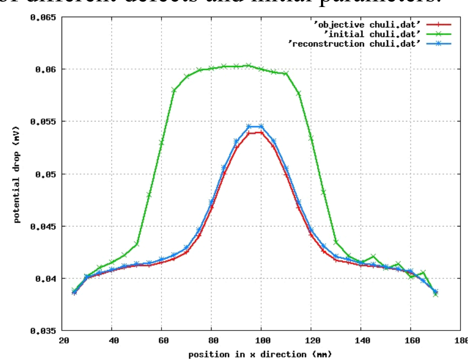


Fig.4 Reconstruction results of NO.1 Specimen

V. Conclusions

In this paper, a quantitative NDT method based on the DCPD technique was proposed and evaluated. At first, a fast forward scheme was introduced to simulate DCPD signals. An inverse algorithm based on the gradient method was adopted to predict the defect profile. Numerical results demonstrated that both the forward and the inverse analysis scheme are efficient for the DCPD signal analysis.

Acknowledgements

This work is supported in part by the National 973 Program of China (No.2007CB707702), National Magnetic Confinement Fusion Science Program of China (No. 2009GB104002) and NSFC (No.50977070).

VI. References

[1] TJ Lu, D. He, C. Chen, The Multi-functionality of ultra-light porous metals and their applications, Advances in Mechanics, Vol.36, 2006, pp. 517-535.

[2] S. Xie, Z. Chen, T. Takagi, Researches on NDT of metallic foam with direct current potential drop method, Int. J. Appl. Electromagn. Mech., Vol.33, 2010, pp.1253-1260.

[3] J. Sheng, Numerical Analysis of Engineering Electromagnetic Field, Xi'an Jiaotong University Press, 1999.

[4] Z. Chen and K. Miya, ECT inversion using a knowledge based forward solver, J. Nondestr. Eval., Vol.17, 1998, pp.167-175.

[5] Z. Chen, et al., Inversion techniques for eddy current NDE using optimization strategies and a rapid 3D forward simulator, Int. J. Appl. Electromagn. Mech., Vol.20, 2004, pp.179-187.