 SL, vol.4, no.2, pp.95-103, 2010

Experimental Study on the Relationship Between PZT Excitation Voltage and Testing Sensitivity of Coating Structures by Electro-Mechanical Impedance Method

Ji-Cheng Li[1], Li Lin[1,2], Di Wu[1], Xi-Meng Li[1] and Ming-Kai Lei[3]

Abstract: Two kinds of plasma sprayed Cr_2O_3 coating specimens are tested by electro-mechanical impedance (EMI) method with PZT patch. Quantitative relationship between PZT excitation voltage and testing sensitivity is investigated in the frequency range of 150-180 kHz. Combined with WK 6500B precision impedance analyzer and self-established high excitation voltage electric impedance measurement system (HEVEIMS), excitation voltages with the range of 0.01 to 20 V are used to excite the PZT patch. As an evaluation indicator of sensitivity, the difference value of one minus correlation coefficient (OMCC) is calculated for each excitation voltage. The results show that in the above frequency range, the OMCC values are not monotonic with the increasing of excitation voltages. The influences of output voltage stability, noise, bonding condition and power consumption of the PZT patch, etc on the sensitivity are generally analyzed. This study provides a guiding reference for the clarification of EMI mechanism as well as the selection of PZT excitation voltage for coating structure characterization with EMI method.

Keywords: Electro-mechanical impedance method; Excitation voltage; Testing sensitivity; Coating; Structure health monitoring

1 Introduction

Thermal barrier coatings (TBCs) are widely used to improve the high temperature and oxidation resistance of metallic materials. Characterization and in-service monitoring of coating morphology, microstructure and mechanical properties has

[1] NDT & E Laboratory, School of Materials Science and Engineering, Dalian University of Technology, Dalian 116024, China
[2] Corresponding author: Li LIN, Dalian University of Technology, Dalian 116024, P.R. China, Tel: 0086-0411-84707117, E-mail: linli@dlut.edu.cn
[3] Surface Engineering Laboratory, School of Materials Science and Engineering, Dalian University of Technology, Dalian 116024, China

significant meanings. Electro-mechanical impedance (EMI) method is a new structural health monitoring technique developed in recent years [Park et al (2003); Yan and Chen (2010)]. It has many advantages such as high sensitivity, anti-interference ability, real-time monitoring of damage development, etc., and has been successfully used in aerospace, civil engineering, precision machinery, and other fields [Yang and Divsholi (2011); Shanker et al (2010); Shin and Oh (2009); Bhalla et al (2009); Park et al (2008)]. However, very little work has been reported on the applications of EMI method to coating materials, since the microstructure and property changes are rather small, and are more difficult to detect. Many studies around this issue should be performed, in particular, how to improve the testing sensitivity of EMI method is an important subject to be focused on. The PZT excitation voltage is an important factor for EMI sensitivity [Liang et al (1996)]. Since the highest excitation voltage of commercial impedance analyzer is typically 1 V, the current study is limited to low excitation voltage range. For example, Raju (1998) tested the damage on bolted aluminum beams at four different excitation voltages from 0.01 to 1V. It is founded that increasing the excitation voltage of PZT patch improves the signal to noise ratio of electric impedance, enhances the capability of identifying weak modes and the sensitivity of EMI method. Little study has been reported on the sensitivity of EMI method at higher excitation voltage, due to the limitation of hardware. Theoretically, at higher excitation voltage, the tested structure is excited more effectively, and the EMI method is more sensitive to minor damages [Liang et al (1996)]. At the same time, the nonlinear performance of PZT patch becomes remarkable since it consumes more power and vibrates intensely. For the inhomogeneous and anisotropic coating materials, the relationship between excitation voltage and the sensitivity of EMI method is very complicated and systematic study should be performed on this issue.

In this paper, a high excitation voltage electric impedance measurement system (HEVEIMS) with the maximum output voltage of 20 V has been established in our lab [Li et al (2012)]. This system can provide 0-20 V PZT excitation voltage at the frequency range of 0-2 MHz. The microstructure changes of plasma sprayed Cr_2O_3 coatings before and after irradiation with high intensity pulsed iron beam (HIPIB) are tested by EMI method. WK 6500B precision impedance analyzer and HEVEIMS are used to measure the electric impedance signals of PZT patch bonded on the upper surface of Cr_2O_3 coatings. The frequency range of 150-180 kHz, in which there is large number of dominant peaks, is chosen for the test. 8 kinds of voltage from 0.01 to 20 V are designed to excite the PZT patch. The impedance signals at 0.01, 0.1, 0.5, 1 V are measured with WK 6500B precision impedance analyzer, and the signals at 5, 10, 15, 20 V are measured with HEVEIMS established in our lab. The difference value of one minus correlation coefficient (OMCC) is employed as a damage indicator to analyze the relationship between excitation voltage and the sensitivity of EMI method quantitatively.

2 Experimental system and specimen

2.1 Experimental system

Two sets of electric impedance measurement system, WK 6500B precision impedance analyzer and HEVEIMS are used in this study. The maximum output voltage of WK 6500B impedance analyzer is 1 V, as shown in Fig. 1, and the testing frequency range is 20 Hz-120 MHz. The image of HEVEIMS established in our lab is given in Fig. 2. This system is composed of personal computer installed with WaveGen-1410 wave generation software, ARB-1410 wave generation card, impedance measurement circuit and DPO-4032 digital oscilloscope.

Figure 1: WK 6500B precision impedance

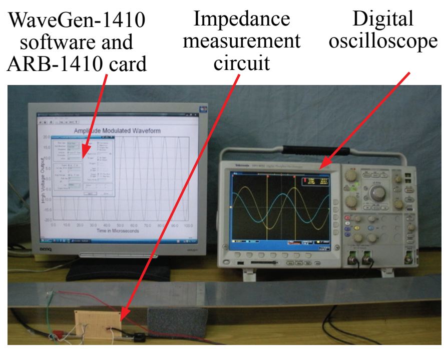

Figure 2: High excitation voltage electric impedance measurement system

2.2 Experimental specimen

The Cr_2O_3 coatings are directly air plasma sprayed on 2 pieces of cleaned and grit blasted heat-resistant steel substrates (50 mm$\times$30 mm$\times$3.5 mm) using a plasma spray equipment (MeTco-Plasma 9MB, USA). The depth of the sprayed Cr_2O_3coatings is about 50 μm. The HIPIB irradiation of the second piece of sample is carried out in a TEMP-6 type HIPIB apparatus at the iron current density of 300A/cm^2, with a shot number of 1.

Fig. 3 presents the cross-sectional SEM images of the as-sprayed and irradiated Cr_2O_3 coatings by HIPIB, respectively. The typical morphology of as-sprayed coating reveals an obvious lamellar structure with many cavities [Fig. 3(a)]. After HIPIB irradiation with 1 shot, a thin discontinuous remelted layer of about 1.5 μm

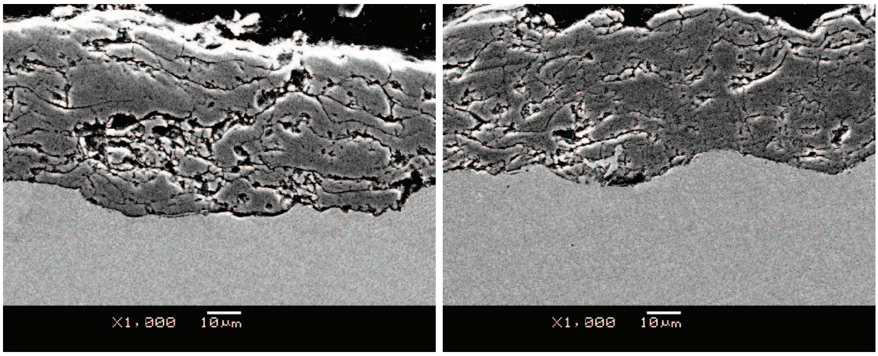

Figure 3: Cross-sectional morphology of the plasma sprayed Cr_2O_3 coatings: (a) as-sprayed; (b) 1 shot by HIPIB

near the surface was observed, which was generated by the locally reformed splats [Fig. 3(b)]. And an apparently compact structure in the matrix coating was formed due to an impact effect of HIPIB irradiation. The number of pores and microcracks decreases obviously. For this study, the mechanical impedance of coating structure is changed, which leads to the changes of PZT electric impedance spectroscopy.

3 Experimental results

To study the influence of PZT excitation voltage on the sensitivity of EMI method, 8 kinds of voltage from 0.01 to 20 V are designed to excite the PZT patch. The frequency range of 150-180 kHz, consists of 151 data points, is chosen for the test. The frequency interval between adjacent points is 200 Hz. The electric impedance signals at the 4 kinds of excitation voltage from 0.01 to 1 V are measured by WK 6500B precision impedance analyzer, which are 0.01, 0.1, 0.5 and 1 V. The electric impedance signals at the 4 kinds of excitation voltage from 1 to 20 V were measured by HEVEIMS, which are 5, 10, 15 and 20 V.

Fig.4 shows the PZT electric impedance results measured in the frequency range of 150-180 kHz. It is observed that the impedance signatures of PZT patch bonded on the Cr_2O_3 coatings before and after irradiation show sharp peaks at various excitation voltages. The peaks correspond to the vibration modes of the local structure around the PZT bonding position. After irradiation by HIPIB, the resonant peaks in the signatures shift 3.6-5.4 kHz to lower frequency and the amplitudes of peaks and valleys are also changed. This indicates the microstructure changes of Cr_2O_3 coatings can be effectively identified by EMI method.

4 Results and discussion

The CC value proposed in Tseng's study [Tseng and Naidu (2002)] is employed to study the relationship between excitation voltage and the testing sensitivity of EMI method, quantitatively. The CC is mathematically defined as

$$CC = \frac{Cov(x,y)}{\sigma_x \sigma_y} \tag{1}$$

$$Cov = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y}) \tag{2}$$

where N is the number of data points in the sampled impedance signatures, x_i and y_i ($i = 1,2,3\cdots N$) are signatures obtained from the PZT bonded to the upper surface of Cr_2O_3 coatings before and after irradiation, respectively. Cov is the covariance of x_i and y_i. σ_x, σ_y and $\bar{x}$, $\bar{y}$ are the standard deviations and mean values of x_i and y_i, respectively. The range of CC value is -1-1. If the two impedance signals in concern are exactly the same, the CC value is 1. In this study, the difference value of one minus correlation coefficient (OMCC) is employed. This is done merely to ensure that with increasing in testing sensitivity, the indicator values also increase.

Fig.5 presents the OMCC values of the PZT electric impedance signatures in the frequency range of 150-180 kHz. It can be observed that at various excitation voltages the OMCC values can give obvious indications on the microstructure changes of Cr_2O_3 coatings after irradiation. The OMCC values show minor fluctuations around 0.52 as the excitation voltages increase from 0.01 to1 V. When the excitation voltages rise from 1 to 5, 10 and 15 V, the OMCC values increase to 0.56, 0.62, 0.73, respectively. Then, the OMCC value decreases to 0.52 for the excitation voltage 20 V.

There are many factors influence the relationship between OMCC values and PZT excitation voltage, such as testing frequency band, output voltage stability, noise, bonding condition and power consumption of PZT patch, etc [Raju (1998); Baptista and Filho (2009); Park et al (2004)]. The relationship is related to the range of excitation voltage. When the excitation voltage increases from 0.01 to 1 V, minor fluctuations are observed in Fig.5. The OMCC values increase gradually with excitation voltage. When the excitation voltage is low, the vibration of PZT film is not sufficient, and the influence of noisy signals becomes obvious. This phenomenon has also been reported in Raju's study [Raju (1998)], as shown in Fig.6. Raju tested the damage on bolted aluminum beams at four different excitation voltages, 0.01, 0.1, 0.5 and 1 V. The results show that at the same damage state, the damage indicator OMCC and the testing sensitivity increase gradually, as the PZT

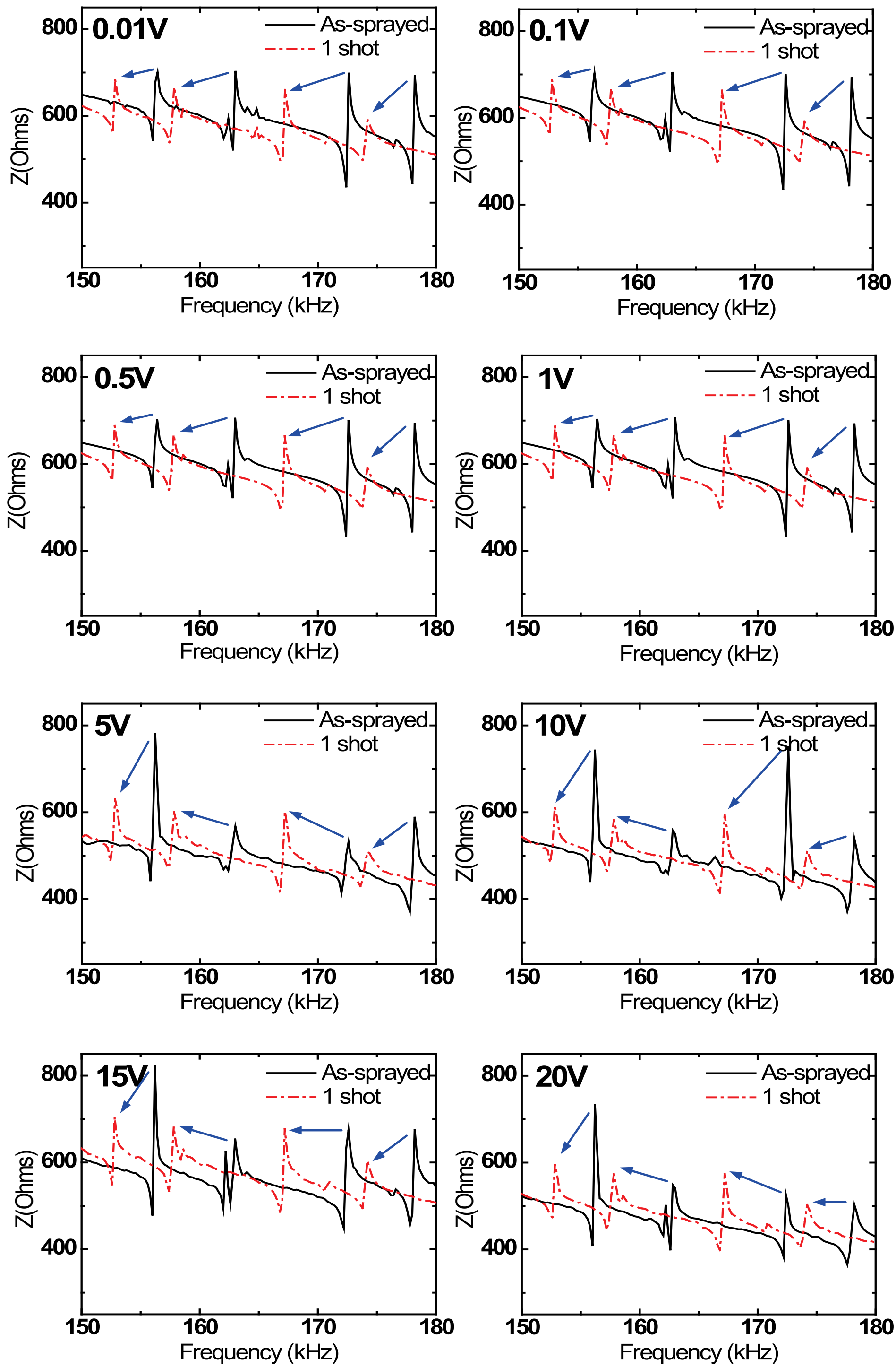

Figure 4: The electric impedance signals with different excitation voltage (150-180 kHz)

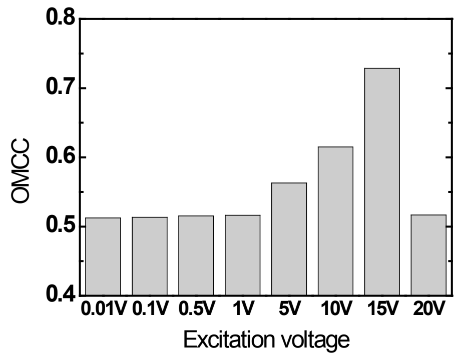

Figure 5: The OMCC values versus PZT excitation voltage at 150-180 kHz

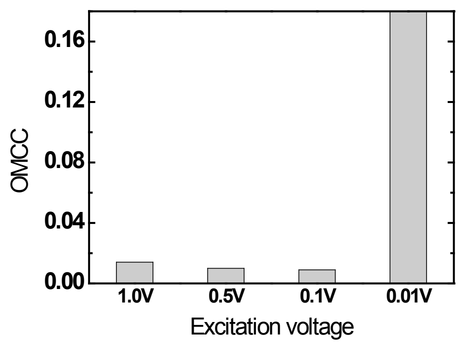

Figure 6: The OMCC values versus excitation voltage given in Raju's study [9]

excitation voltage increases from 0.1 to 1 V. The change of OMCC values is not very significant, and is about 0.01. When the excitation voltage is as low as 0.01 V, the resulting impedance signal is well into the noise region, and the OMCC value is much larger than the other three excitation voltages because of the influence of noise. In this study, when the excitation voltage decreases to 0.01 V, some noise signals can also be founded in Fig.4. The impedance curve is not very smooth and there are small impedance peaks induced by noise signals. These characteristics can not be observed at other excitation voltages. Therefore, when commercial impedance analyzer is used in EMI study, a higher excitation voltage should be used to obtain larger sensitivity and avoid noise interference.

When the excitation voltage increases from 1 to 15 V, the OMCC values increase monotonically with excitation voltage. This indicates the testing sensitivity of EMI method can be significantly increased by using a higher excitation voltage. While the sensitivity decreases obviously when the excitation voltage further increases to 20 V. At high testing frequency range, the PZT patch consumes more power, and a higher stability of output voltage is required for ARB-1410 wave generation card. Meanwhile, the vibration of PZT patch is more serious, and the PZT is very sensitive to the bonding condition. The PZT impedance signals are more susceptible to noise interference. Sun et al (1995) pointed out that 15 V is the top limit of PZT's linearity. In this study it is also found that, when the output voltage of ARB-1410 wave generation card increases to 25 V and the testing frequency is higher than 500 kHz, serious distortion occurs on the output waveform since the output power is too large. Therefore, the impedance measurement accuracy decreases at such high voltage. This indicates the increase of testing sensitivity with excitation voltage also has some limits at high testing frequency ranges. Further studies are in progress to address the changes of EMI testing sensitivity at higher excitation voltages.

5 Conclusions

This paper tests the microstructure changes of Cr_2O_3 coatings before and after irradiation with HIPIB by EMI method. The relationship between PZT excitation voltage and testing sensitivity of EMI method is quantitatively analyzed in the voltage range of 0.01 to 20 V, with WK 6500B precision impedance analyzer and HEVEIMS. The results show that the microstructure changes of Cr_2O_3 coatings after irridiation can be effectively tested by EMI method. The PZT excitation voltage is an important factor for EMI sensitivity, and the sensitivity is not monotonic with the increasing of excitation voltage in the frequency range of 150-180 kHz. At a given frequency range, the sensitivity can be further improved by using a high excitation voltage. The interaction mechanism between PZT excitation voltage and testing sensitivity of EMI method needs further study.

Acknowledgement: This work is supported by the National Basic Research Program of China under Grant No.2009CB724305.

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