Monitoring the integrity of massive aluminum structures using PZT transducers and the technique of impedance

Rosalba da Costa*[a], Joaquim M. Maia[b], Amauri A. Assef[a], Sergio F. Pichorim[b], Eduardo T. Costa[c], Vera L. S. N. Button[c]

[a]DAELT/CPGEI; [b]DAELN/CPGEI, Federal University of Technology – Paraná - UTFPR, Av. Sete de Setembro, 3165, Curitiba, PR, Brazil 80230-901; [c]DEB/FEEC-CEB, State University of Campinas - UNICAMP, Cidade Univ. Zeferino Vaz, PO Box 6040, Campinas, SP, Brazil 13083-970

ABSTRACT

Safety, performance, economy and durability are essential items to qualify materials for the manufacturing of structures used in different areas. Generally, the materials used for this purpose are formed by composites and sometimes they can present failure during the manufacturing process. Such failures can also occur during use due to fatigue and wear, causing damage often difficult to be visually detected. In these cases, the use of non destructive testing (NDT) has proven to be a good choice for assessing the materials quality. The objective of this work was the electromechanical impedance evaluation of massive aluminum structures using ultrasonic transducers to detect discontinuities in the material. The tests have been done using an impedance analyzer (Agilent 4294A), an ultrasound transducer (1.6 MHz of central frequency), two types of PZT ceramics (0.267 mm and 1 mm thickness) and four aluminum samples (250 x 50 x 50 mm) with the transducer placed at three different regions. One sample was kept intact (reference) and the others were drilled in three positions with different sizes of holes (5 mm. 8 mm and 11 mm). The electromechanical impedance was recorded for each sample. The root mean square deviation index (RMSD) between the impedance magnitude of the reference and damaged samples was calculated and it was observed an increase in the RMSD due to the increase of the diameter of the holes (failures) in the samples completely drilled. The results show that the proposed methodology is suitable for monitoring the integrity of aluminum samples. The technique may be evaluated in characterizing other materials to be used in the construction of prostheses and orthoses.

Keywords: Damage condition, electromechanical impedance, PZT ceramics, RMSD index, NDT

1. INTRODUCTION

Actually, several types of periodic inspections using a Non-destructive Test (NDT) are offered to monitor structures in order to ensure enough security and to avoid unnecessary maintenance procedures that can result in costly financial expenses. Obsolete products are discarded daily in engineering to give space to the structures composed by leagues of smart materials of high resistance to the gradual effects of the time and to the functional stress. Therefore, the same technological advancement takes place in parallel with the search of the development of devices able to monitor such compounds.

Pointed as one of the most efficient and safe NDT methods, the ultrasonic (US) transducers using Phased Array technology have their applications not limited only to the medical area, but they are also used in monitoring several types of structures[1]. Favored by this aspect, several areas of the engineering are using the ultrasound as an inspection technique for detecting flaws, cracks and any other type of abnormality that could reduce the time of useful life of the structures.

Because of presenting the piezoelectric property susceptible to the electromechanical variation within a certain range of temperature and frequency, the ultrasonic method allows easy adaptation to being associated with other techniques in order to provide bigger specificity in the evaluation of the data obtained by this one[2-5]. Of many quite succeeded techniques applied using the ultrasound, there is an outstanding Electromechanical Impedance Technique (EMI) [6].

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*rosalbautfpr@gmail.com; phone +55 41 3310-4698; fax +55 41 3310-4683; www.utfpr.edu.br

Structural Health Monitoring and Inspection of Advanced Materials, Aerospace,
and Civil Infrastructure 2015, edited by Peter J. Shull, Proc. of SPIE Vol. 9437,
943728 · © 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2084397

This work aims to implement and evaluate a monitoring methodology that uses the EMI and the Root Mean Square Deviation[7] (RMSD) index to characterize massive aluminum samples.

2. METHOD USED FOR CHARACTERIZATION OF MASSIVE ALUMINUM USING ULTRASOUND

The ultrasonic wave is characterized by the reflection and refraction effects while propagating through media with different acoustic impedances. Such properties allow the use of the ultrasound in the application of transmission-reception and pulse-echo methods in the characterization of biological and non-biological media. These methods applied together can provide data as the propagation velocity and attenuation of ultrasonic wave, allowing the characterization of these media[8]. However, other ultrasound techniques can be used for material characterization, such as the EMI.

The EMI technique is based on the measurement of impedance value of the electromechanical structures using piezoelectric ceramics or transducers operating at a frequency higher than 20 kHz[9-10]. The principle of this technique is based on the piezoelectric effect, which has a property of converting mechanical energy into electric, the direct piezoelectric effect, Eq. (1), and to turn the electric energy into mechanical, known as the inverse piezoelectric effect, Eq. (2). The direct piezoelectric effect is related to the electric displacement D suffered by the particles due to the polarization of the electric field E, which turns into a stress S, where d is the piezoelectric coefficient and ε is the permittivity of the medium. The inverse piezoelectric effect is characterized by the application of a mechanical stress S on the solid, which produces a strain S and an electric displacement of the charges that generates an electric field E, in which g is the compliance of the medium[11].

$$D = dS + \varepsilon E \tag{1}$$

$$T = gS + dE \tag{2}$$

The ultrasound technique allows obtaining the data in real time, besides acting in the acoustic impedance of the medium being monitored. This property contributes in the identification of the structure, as it directly influences the intensity of the reflected signal[5,12]. The piezoelectric transducer, when coupled to the structure being monitored, causes an interaction between the electric impedance and the mechanical impedance of the structure. As from the changes in the mechanical impedance of the structure, failures in the process of manufacture, stresses or corrosion can be detected through the measurement of the electric impedance of the transducer subject to an appropriate frequency range[12]. This technique uses the analysis of comparison between the values obtained in the measure of the electric impedance (amplitude and phase) of the reference structure and the electric impedance of the monitored sample. So, this procedure of monitoring is appropriate to detect fatigue, cracks and faults in the composition of aluminum bars or metal plates, as well as several types of simulated damages.

Currently, the EMI technique is also applied to analyze the correct sizing of PZT pads with the purpose of optimizing the sensibility of the transducer to detect damages in the aluminum plates[13]. The obtained results showed that the geometry, the thickness and the size of the PZT pads influence the accuracy of the analysis. PZT small size ceramics promote a low static capacitance and high amplitude in the electric impedance that allows the acquisition of good results in the use of the EMI technique and the calculation of the Root Mean Square Deviation (RMSD) index. The RMSD index is used widely in the detection and quantification of faults in structures because it presents high sensibility to the variation of the electric impedance[14].

3. METHODOLOGY

In this study, it was evaluated a material characterization method that includes the calculation of the RMSD index in the measurements of the electromechanical impedance of ultrasound transducers coupled to massive aluminum structures from which different failures of dimensions were inserted.

Fig. 1 presents the block diagram of the setup used to carry out the data acquisition of EMI in aluminum samples. The system is composed by an impedance analyzer (Agilent 4294A) and four aluminum samples (50 x 50 x 250 mm). The tests were carried out using an ultrasound transducer (FUNBEC, 15700IH, 1.6 MHz of central frequency) and PZT 855 ceramics discs (APC International Ltd) 12.70 mm x 0.267 mm and of 12.70 mm x 1.00 mm that were coupled to the samples using epoxy. One of the aluminum samples was maintained intact to serve as a reference (REF) and the others were drilled in three different positions, with holes of 5 mm, 8 mm and 11 mm (Fig. 2).

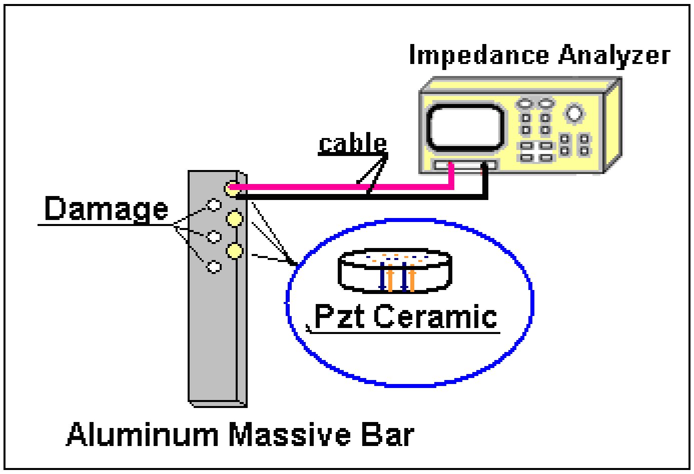
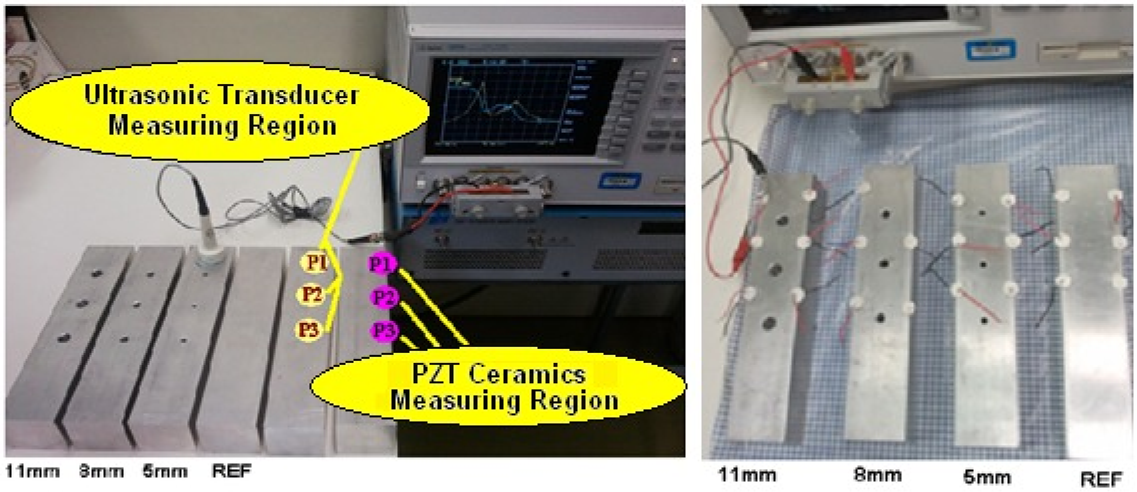


Figure 1. Block diagram of the setup used to measure the electromechanical impedance of PZT ceramics coupled to the aluminum massive bars samples.



(a) (b)

Figure 2. Arrangement used to detect damage on aluminum massive bars. (a) Electromechanical impedance measurement with the ultrasonic transducer of 1.6 MHz central frequency, showing the positions where the measurements have been done. (b) PZT ceramics discs coupled to the samples using epoxy.

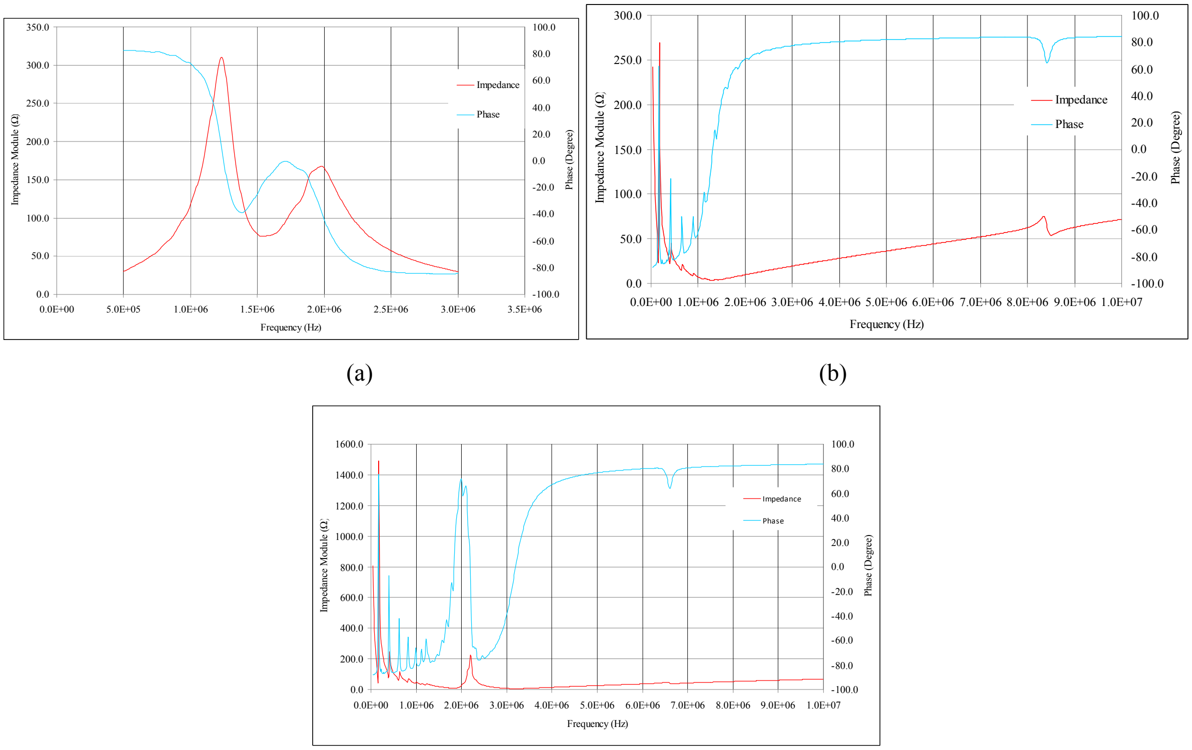
In the regions P1, P2 and P3 there were measured the EMI (amplitude and phase) as a function of the frequency, in the range 0.5 - 3 MHz for the FUNBEC transducer. Five measurements were carried out in each position and the mean value of them were used. The same procedure was carried out whit the two types of PZT ceramics, in the range between 40 kHz and 1 MHz, correspondent to the radial propagation mode of the ceramic discs. All the tests were carried out at the room temperature of approximately 25 ^{o}C, however this methodology does not suffer the influence of small temperature variations[15].

The data from the impedance analyzer were transmitted to a microcomputer via Ethernet interface to be processed using the Excel program (Microsoft Inc.). The *RMSD* index (Eq. 3), used to quantitatively determine the existence of the damage in the structure, was calculated between the EMI values of the reference and the damaged samples. The electric impedance (magnitude, real part or imaginary) $Z_{n,h}$ is related to the reference structure, while the $Z_{n,d}$ refers to the value of the impedance of the damaged structure, n corresponds to the obtained measure and p is the total number of measurements that compose the frequency range used in the data acquisition system.

$$RMSD = \sum_{n=1}^{p} \sqrt{\frac{\left(Z_{n,d} - Z_{n,h}\right)^2}{\left(Z_{n,h}\right)^2}} \tag{3}$$

4. RESULTS

Fig. 3 presents the free probes electric impedance measurements for the ultrasound transducer (Fig. 3(a)), the PZT 0.267 mm thickness (Fig. 3(b)) and the PZT 1.0 mm thickness (Fig. 3(c)). It is possible to see that the PZT discs presents some resonance frequencies in the range between 40 kHz and 10 MHz, corresponding to the radial (lower frequencies), axial (higher frequencies) and other displacement modes (intermediate frequencies), while the ultrasound transducer presents the main resonance frequency close to 1.6 MHz. In this work, the tests have been done using a range that includes the transducer central frequency (500 kHz - 3.0 MHz) and in the range 40 kHz - 1.0 MHz for the PZT ceramic discs of 0.267 mm and 1.0 mm thickness.

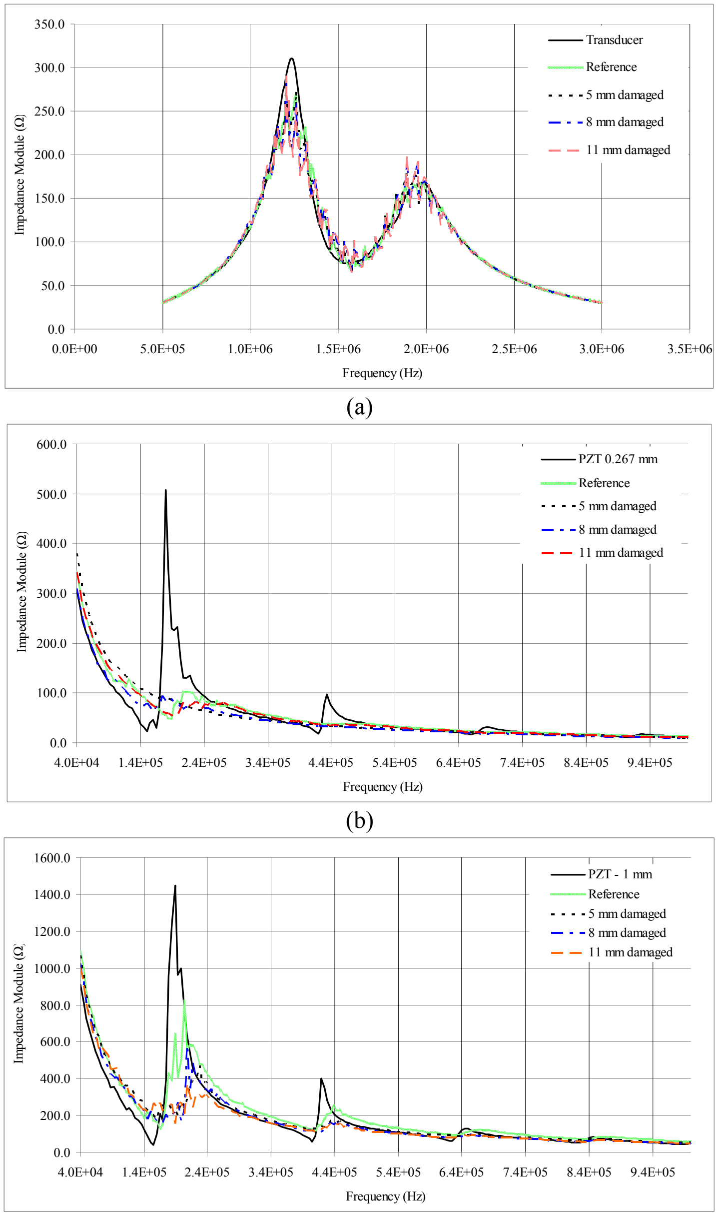


(a) (b)

(c)

Figure 3. Impedance module and phase of the electromechanical impedance as a function of the frequency for the free probes: (a) Ultrasonic transducer; (b) PZT ceramics discs of 0.267 mm thickness and (c) PZT ceramics discs of 1 mm thickness.

Fig. 4(a) presents an example of the results of the EMI amplitude obtained with the transducer placed in the position P1 of the samples. The first curve (Transducer) corresponds to the measurement of the acoustic impedance of the transducer separately (without coupling with the samples) and the others correspond to the measurements of the reference (Reference) and the damaged samples with holes of diameters 5 mm, 8 mm and 11 mm, respectively. Fig. 4(b) and 4(c) present the results obtained for the tests in the position P1 using the 0.267 mm and 1 mm ceramic discs, respectively.



(a)

(b)

(c)

Figure 4. Impedance module of the electromechanical impedance as a function of the frequency obtained with the (a) Ultrasonic transducer; (b) PZT ceramics discs of 0.267 mm thickness and (c) PZT ceramics discs of 1 mm thickness. The first curve in the legend correspond to the free probes (Transducer, PZT - 0.267 mm and PZT - 1 mm) positioned in the region P1 of the four aluminum samples (Reference and damaged using 5 mm, 8 mm and 11 mm holes).

It can be seen in Fig. 4, that in some frequencies, mainly in the range of the transdutor resonance frequency (1.6 MHz), there is a reduction of the impedance with the increase of the diameter of the flaws. Similar results were obtained using the 0.267 mm and 1 mm thickness PZT ceramics discs. However, this relationship is clearer in the frequency range of 200 - 440kHz, which correspond to the radial module of PZT discs.

Fig. 5 shows the RMSD index results obtained for the data shown in the graphs of Fig. 4. There was an increase in the value of the RSMD index in accordance with the increase in the diameter of the damages in the samples.

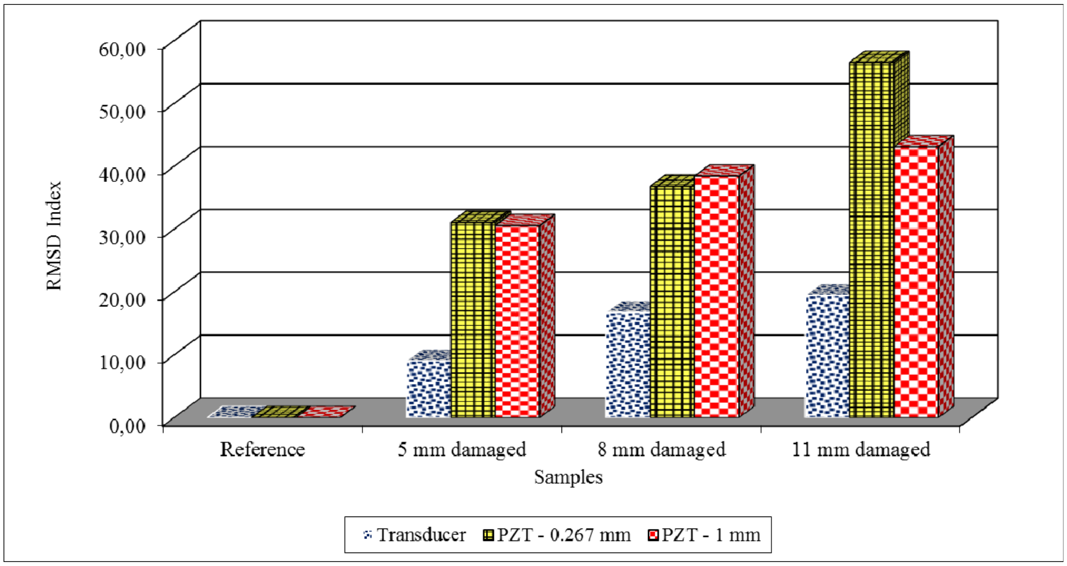


Figure 5. EMI RMSD index calculated between the reference (Reference) and damaged aluminum samples with 5 mm (5 mm damaged), 8 mm (8 mm damaged) and 11 mm (11 mm damaged). The transducer and the PZT ceramic discs of 0.267 mm and 1 mm thickness were placed at the position P1 of the four evaluated samples.

5. CONCLUSION

This study evaluated the efficacy of the EMI measurement technique along with the calculation of the RMSD index for the characterization of aluminum samples with the presence of failures of different sizes. The results obtained in this study are consistent with those found by other authors[6,12]. They evaluated other types of materials and noticed that the electromechanical impedance is an appropriate method to identify flaws in massive structures such as aluminum samples, material widely used many areas such as, for example, the construction of airplanes, in the naval companies and in the Biomedical Engineering.

The application of this methodology can help in the failure detection in the composition in aluminum samples used in the manufacture of rods and joints of prostheses and orthotics[16]. Because of being lighter, the aluminum is used widely in the composition of exoskeletons (forearm, hands and others)[17]. However, the continuous movement in determined regions of the device can produce stresses that, generally, are not visibly detected by the user, but they can be identified using the methodology proposed in this study.

Future researches will be carried out to evaluate the efficacy of other propagation modes (e.g. axial mode) of the PZT ceramics discs and to evaluate the application of the technique in the characterization of other biological and non-biological materials.

The results obtained in this study allowed concluding that the EMI measurement technique using an ultrasound transducer or PZT ceramic discs coupled to massive aluminum samples was effective in the identification of irregularities in the samples. The RMSD index presented increasing relationship with the increase in the diameter of the samples damages, indicating that the method presents promising results to be applied in the characterization of other types of biological (e.g. bones) and non-biological materials (thermoplastics, alloys and others).

ACKNOWLEDGEMENT

To CNPq, Fundação Araucária, CAPES and FINEP for the financial support to this work. To DEB/FEEC/UNICAMP and BIOTA/CPGEI/UTFPR for the probes and the equipment that have been used and to DAMEC/UTFPR for sample preparation.

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