ABSTRACT

Experimental results obtained during fatigue testing of a spot-welded lap-shear structural-joint specimen are presented. In these experiments, the electro-mechanical (E/M) impedance technique was used for structural health monitoring, damage detection, and NDE. The test specimens were instrumented with piezo-electric wafer transducers, and the base E/M impedance signature was recorded over the relevant frequency range. Fatigue testing was applied to initiate and propagate crack damage of controlled magnitude. Preliminary tests were performed to correlate stiffness decrease with damage progression and remaining life. Then, during the health monitoring tests, the specimens were continuously monitored for stiffness decrease indicative of damage. E/M impedance signatures were periodically recorded, as the damaged progressed. Signature data was processed, and the damage index was calculated. The initiation and propagation of damage, i.e., structural crack, was successfully correlated with the E/M impedance measurements. Damage index values were observed to increase as crack damage increases. Sensing and the localization principles of E/M impedance NDE method were confirmed. Rejection of spurious information was also confirmed. Through these experiments, the E/M impedance technique has been, once again, proved to be a powerful tool with good potential for damage detection, health monitoring, and NDE.

1. INTRODUCTION

Health monitoring of structural joints is a major concern of the engineering community. Among joining techniques, the spot welding and weldbonding (spot weld + adhesive bonding) are widely used in a number of industries. Spot welding is the traditional method of assembly for steel-based automotive structures, while weldbonding is a novel technique that combines the stiffness and productivity benefits of adhesive bonding with the proven-technology attributes of spot welding. Future trends in the design and construction of vehicular structures indicate a strong diversification of material usage, with aluminum and polymeric composites projected to play a major role. While aluminum is amenable to both spot welding and adhesive bonding, composites will, most likely, be entirely adhesive bonded. The trend towards adhesive bonding and weldbonding replacing traditional joining methods is clearly perceived.

In a previous paper, Giurgiutiu et al. (1997) performed a review of current NDE methods applicable to spot welded and weldbonded joints. However, none of them were found to be well suited for the present-day requirements for in-situ health monitoring and on-line failure prevention. In the same paper, concepts for adaptive structural health monitoring of this type of joints were developed. In the present paper, experimental results obtained on lap shear specimens of spot-welded joints, using the electro-mechanical (E/M) impedance technique for structural health monitoring, damage detection, and non-destructive evaluation (NDE) will be presented.
2. ELECTRO-MECHANICAL IMPEDANCE

The electro-mechanical impedance method for structural health monitoring, damage detection and NDE was explained in detail by Rogers and Giurgiutiu (1997) and by Giurgiutiu and Rogers (1997). A overview of its principles is given next. Consider a piezo-electric transducer wafer intimately bonded to the surface of a structural member. When excited by an alternating electric voltage, the piezo-electric transducer applies a local strain parallel to the surface. Thus, elastic waves are transmitted into the structure. The structure responds by presenting to the transducer the drive-point mechanical impedance $\omega \left( Z_{str} \right) = i \omega m_c (\omega) + c_e (\omega) - i k_{str} (\omega) / \omega$. Through the mechanical coupling between the PZT transducer and the host structure, and through the electro-mechanical transduction inside the PZT transducer, the drive-point structural impedance directly reflects into the effective electrical impedance as seen at the transducer terminals (Figure 1).

\[
Z(\omega) = \left[ i \omega C \left( 1 - \kappa_{31}^2 \frac{Z_{str}}{Z_{PZT} + Z_{str}} \right) \right]^{-1}. \tag{1}
\]

Here, $Z(\omega)$ is the equivalent electro-mechanical admittance as seen at the PZT transducer terminals, $C$ is the zero-load capacitance of the PZT transducer, $\kappa_{31}$ is the electro-mechanical cross coupling coefficient of the PZT transducer ($\kappa_{31} = d_{31} / \sqrt{\varepsilon_{33}}$), $Z_{str}$ is the impedance of the structure, and $Z_{PZT}$ is the impedance of the PZT transducer. The electro-mechanical impedance method is applied by scanning a predetermined frequency range in the hundreds of kHz band and recording the complex impedance spectrum. By comparing the impedance spectra taken at various times during the service life of a structure, meaningful information can be extracted pertinent to structural degradation and the appearance of incipient damage. It must be noted that the frequency range must be high enough for the signal wavelength to be significantly smaller than the defect size.

A qualitative estimation of the structural health can be rapidly achieved through the damage index (Rogers and Giurgiutiu, 1997). The damage index is a scalar quantity that serves as a metric of the damage that is taking place in the structure. A convenient damage index can be based on the Euclidean norm, i.e.,

\[
DI = \sqrt{\frac{\sum_{n=1}^{N} \left[ \text{Re}(Z_i^n) - \text{Re}(Z_i^0) \right]^2}{\sum_{n=1}^{N} \text{Re}(Z_i^0)^2}}. \tag{2}
\]

In Equation (2), $N$ is the number of sample points in the spectrum, and the superscript 0 signifies the initial (baseline) state of the structure.

3. SPOT-WELDED LAP-JOINT SHEAR SPECIMEN

3.1. Description of the Specimen

A spot welded lap-joint shear specimen was used in this experiment (Figure 2). The lap joint was constructed from dissimilar alloys, aluminum 7075-T6 and 2024-T3. The particular combination of materials chosen is of interest for the production of built-up skin-stringer structure for aerospace applications. Nominal thickness of the specimen was 2 mm (80-mil). Specimen width was 25.4 mm (1-in) and length 167 mm (6.5-in). The overlap length was 36 mm (1.5-in). Spot weld size was 9 mm (0.354-in).

![Figure 2 Spot-welded lap-joint specimen instrumented with 12 PZT wafer transducers. The numbers represent the transducer stations arranged in flip-side pairs on the specimen.](image-url)
3.2. Instrumentation of the Specimen

The specimen was instrumented with 12 square-shaped piezo-electric wafer transducers of 6-mm (1/4-in) size (Figure 2). The wafer transducers were manufactured in the Laboratory for Adaptive Material Systems and Structures (LAMSS), Department of Mechanical Engineering, University of South Carolina. Piezoelectric transducer was fabricated from PZT (Lead Zirconate Titanate) single sheets supplied by Piezo Systems, Inc., Part # T107-H4ENH-602. The as-supplied PZT sheets were of dimensions 2.85-in × 2.85-in (72 mm × 72 mm) and had a thickness of 190 µm (7.5-mil). The sheets were cut into 6 mm strips, and then into small (6 mm × 6 mm) PZT squares using proprietary methods. The small PZT squares were affixed onto 25-µm (1 mil) copper foil using proprietary bonding methods. The assembled transducer was mounted onto the specimen using Micro Measurements, Inc. strain-gauge-mounting technology.

The transducers were wired and numbered. Through the process, the electrical integrity of the transducers was measured for consistency. Rejects were dismounted and re-instrumented. Finally, support fixtures and the clip-on displacement transducer were attached. The instrumented specimen is presented in Figure 3. Using an Hewlett Packard 4194A Impedance Analyzer, the E/M impedance signatures of the 12 PZT transducers affixed to the specimen was taken and stored in the PC as baseline information. The frequency range 200 to 1100 kHz was determined as best suited for this process.

4. EXPERIMENTAL PROCEDURE

4.1. Loading Conditions

The spot-welded lap-joint specimen was mounted into an MTS 810 Material Test System as shown in Figure 4. Tension-tension fatigue testing at R=0.1 and a max load of 2.67 kN was performed. The load path in the lap-joint specimen is eccentric and produces a combined tension-bending load condition. The typical ultimate load for the spot weld specimens is approximately 8 kN. Under this set of fatigue loading, the average fatigue life is approximately 45,000 cycles.

4.2. Generation of Controlled Damage

Generation of controlled damage in the specimen is a major concern for any health monitoring and damage detection experiment. In the present study, our primary goal was to correlate changing E/M impedance signals with varying levels of fatigue damage in the spot welded joint. Hence, a repeatable method of identifying and quantifying specimen damage at any point in time was required.

4.2.1. Nature of Damage

In the spot-welded lap-joint specimen, fatigue cracks develop as follows: A surface crack initiates at the weld nugget/base metal interface in the 7075-T6 half of the weld specimen. Then, the surface crack grows around the periphery of the weld nugget while at the same time growing through the sheet thickness.
After the crack penetrates the sheet, it extends in the same manner as a through crack in a center-cracked plate. At the load levels used in this study, the great majority of fatigue life is consumed before the crack penetrates the sheet thickness. In some cases, overload fracture will occur before the crack penetrates the sheet thickness. Figure 5 is a visible light optical fractograph showing the general shape of the fatigue crack in one half of a fractured overlap shear spot weld specimen. The initiation site is on the original faying surface of the welded specimen and the black line separates the fatigue failure from the overload fracture.

4.2.2. Damage Quantification and Control

Damage quantification and control was performed using stiffness-damage correlation principle. It has long been known that a direct correspondence exists between stiffness loss in a fatigue specimen and damage progression under repetitive (fatigue) loading. Razvan, Reifsnider, and Elahi (1994) have shown that a direct relationship can be established between stiffness reduction and damage progression in materials under cyclic loading. Hence, dynamic characterization can be implemented during fatigue testing to estimate the extent of crack progression and the remaining life of the structure. Although spot weld fatigue tests are typically used to develop S-N data, it was surmised that fatigue damage could be monitored by observing changes in specimen stiffness as a function of fatigue cycles. Previous studies have shown stiffness changes in spot-welded structure; however, these studies typically used machine ram displacement rather than actual specimen displacement resulting in some anomalous and misleading stiffness vs. life correlation (Salvini et al., 1997).

In our experiments, we generated controlled damage through fatigue loading and stiffness monitoring. Real time monitoring of specimen stiffness was done using the load signal from the MTS force gauge and the displacement signal from the clip-on gauge placed across the spot weld (Figure 3). The load signal and the displacement signal are processed using a fatigue crack growth test control and data acquisition program originally designed to monitor specimen compliance for determination of crack length in da/dN-∆K testing. The result is a nearly continuous record of specimen stiffness as a function of fatigue life.

![Figure 5 Visible light optical photograph of the fatigue fracture in a spot weld. The black line outlines the region of fatigue failure.](image)

![Figure 6 Graph of percentage stiffness loss vs. percentage cycles to failure for lap-shear spot weld specimens tested at P_max=2.7 kN and R=0.1](image)

While both spot weld fatigue life and initial spot weld stiffness exhibit significant scatter, previous testing (Chassereau and Reynolds, 1998) has shown that a simple normalization procedure can be used to collapse all the data from tests performed under a single set of conditions. By dividing the instantaneous values of stiffness loss and fatigue cycles, normalized by the initial stiffness and by the fatigue cycles to failure, respectively, we generated “% stiffness loss” and “% cycles to failure”. After normalization, the results from several fatigue tests fell into a narrow scatterband (Figure 6). Thus, a one-to-one correspondence between stiffness loss in the specimen and accumulated cycles to failure (i.e., damage) was established.

4.3. Health Monitoring under Controlled Damage Conditions

The stiffness-damage correlation principle was used to identify and control the damage progression in the spot-welded lap-joint shear specimen during the fatigue testing. Our purpose was to stop the loading and collect health-monitoring data at predetermined damage values. This was achieved by monitoring the stiffness decrease during fatigue cycling, and stopping the experiment at values of
95%, 90%, 80%, 70%, 65%, 60%, 55% of initial stiffness. These stiffness values were interpreted to correspond to 5%, 10%, 20%, 30%, 35%, 40%, and 45% damage.

Fracture

Transducer #1, placed on the top plate, in the load path, next to the fracture line
(Transducer #0 is placed on the flip side of the specimen, on the unloaded overhang)

Fracture

95%, 90%, 80%, 70%, 65%, 60%, 55% of initial stiffness. These stiffness values were interpreted to correspond to 5%, 10%, 20%, 30%, 35%, 40%, and 45% damage.

At each stiffness value, readings were taken of the E/M impedance signature of the 12 PZT transducers and stored in the PC. The process was repeated until the specimen broke at 32,260 cycles, after its stiffness reduced to 54% of the initial value. The stiffness-life data points obtained in this experiment were superposed (plotted as circles) on the stiffness-life correlation curve of Figure 6 that already contained results from three previously performed fatigue tests on similar specimens under similar loading (plotted as crosses). As shown, the current experiment fits perfectly into the general trend, and the stiffness-life correlation assumption can be fully trusted.

5. CORRELATION OF E/M IMPEDANCE READING WITH STIFFNESS REDUCTION AND DAMAGE PROGRESSION.

Examination of the E/M impedance data revealed that the signatures change significantly with the damage progression. The space of this short paper is insufficient to present the results obtained with all the 12 E/M transducers. Hence, attention will be focused on two transducers: #1 and #0. Recall (Figure 2) that these transducers are placed next to the spot weld, on the longitudinal axis of symmetry of the specimen. However, #1 transducer is in the load path, while #0 transducer is outside the load path, on the overhang adjacent to the spot-weld (Figure 7). Data for #1 transducer are presented in Figures 8 and 9.

Figure 7 Post-failure presentation of the spot-welded lap-joint shear specimen. Failure occurred after \( N = 32,260 \) cycles, at 54% stiffness.

Figure 8 Superposed plots of impedance signatures of E/M transducer #1 for increasing amounts of structural damage (available for viewing in color at [http://www.engr.sc.edu/research/lamss/spot1a.htm](http://www.engr.sc.edu/research/lamss/spot1a.htm)).

Figure 8 presents the superposed plots of impedance signatures of #1 transducer for increasing amounts of structural damage. The real part of E/M impedance is plotted against frequency in the 200 – 1100 kHz bandwidth. Figure 9 gives a plot of the damage index versus percentage structural damage. Examination of Figure 8 indicates that significant changes took place in the E/M impedance signature as damage progressed through the specimen. These qualitative observations are transformed into quantitative data through the Damage Index (Figure 9).

Examination of Figure 9 indicates that the damage index increases as the structural damage increases. This shows that the damage index, calculated with formula (2),
is a valid quantitative indicator of the amount of structural damage adjacent to the transducer. Thus, both the sensing and the localization principles of E/M impedance NDE method are confirmed. The quantitative information given by the damage index can be usefully leveraged into life prediction studies.

Examination of transducer #0 revealed a different behavior. E/M impedance signature and damage index plots (for brevity, not shown here) indicate much less modification with damage progression. This is entirely explainable, since transducer #0 is placed on an overhang region outside the load path. Hence, the structural region monitored by transducer #0 is not undergoing damage during fatigue testing, and its E/M impedance signatures and damage index values are not expected to change during these tests. This observation confirms the localization and rejection principles of the E/M impedance method.

6. CONCLUSIONS

An important application of the E/M impedance method to the health monitoring, damage detection, and NDE of spot-welded structural joints has been presented. Incremental damage tests of spot-welded lap-joint shear specimens under fatigue loading were performed. The stiffness-damage correlation principle was used to quantify progression of damage. Experimental data collected in these tests showed that the E/M impedance signature, and the resulting damage index, could be directly correlated with the structural damage progression. Through the use of multi-site E/M impedance measurements, the sensitivity, localization, and rejection properties of the method have also been verified. The data presented in this paper indicate that:

1) Specimen stiffness may be used as a measure of spot-weld fatigue damage.
2) Reproducible amounts of fatigue damage can be introduced in the specimen. Thus, NDE techniques can be calibrated.
3) The E/M impedance data correlates with the damage level in the spot weld.
4) Changes in E/M impedance signatures from individual PZT transducers depend on transducer position relative to the damage site. Thus, a transducer array can be devised to provide information on both the level and the location of damage.
5) The correspondence between remaining life and stiffness loss observed for several different loading levels in spot-welded specimen (Chassereau and Reynolds, 1998) can be extended to any repetitive fatigue-loading spectrum. Thus, the E/M impedance method can be calibrated to indicate the remaining life of the structure for a given loading spectrum.

The work presented in this paper indicates that the E/M impedance data may be successfully used for health monitoring and remaining fatigue life estimation of spot-welded structural joints. In-situ arrays of E/M transducers placed on aging structures are envisioned. Through local-area data collection, interpretation, and wide-area tele-transmission, an automatic system for health monitoring and damage detection can be devised and installed. However, significant work still needs to be done to ensure consistency, reliability, and market acceptability of this method. Directions for further work include perfection of sensors, miniaturization of impedance measuring apparatus, and development of a data-gathering network. Such work is currently under way, and will be the subject of future reporting.

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8. REFERENCES