Submitted to the 1997 ASME International Mechanical Engineering Congress and Exposition, Dallas, TX, Nov. 16-21, 1997

ADAPTIVE HEALTH MONITORING CONCEPTS FOR SPOT-WELDED AND WELD-BONDED STRUCTURAL JOINTS

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ABSTRACT

The health monitoring of structural joints is a major concern of the engineering community and needs to be addressed with the proper consideration. Among joining techniques, the spot welding and weld-bonding (spot weld + adhesive bonding) methods are of great interest in a number of industries. Spot welding is the traditional assembly method for steel-based automotive structures, while weld-bonding 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. Hence, the trends towards weld-bonding and adhesive bonding are clearly visible.

The paper first presents a short review of the present trends in joining techniques with special emphasis on those in present and future use in the automotive industry. This will be followed by a short review of the existing non-destructive evaluation (NDE) techniques that may be applicable to the health monitoring of spot welded and weld-bonded structures. Next, novel concepts of health monitoring utilizing an adaptive structures approach are presented. Laser ultrasound techniques; tagged adhesive methods; dielectric response techniques; electric potential methods, etc. are briefly mentioned.

Particular emphasis is placed on the electro-mechanical impedance method. This novel method is described in some detail. The electro-mechanical impedance method utilizes the coupled electro-mechanical response of piezo-electric interrogators (sensor-actuator crystals) intimately bonded to the monitored structure. An array of such structural interrogators can be envisaged to monitor the incipient local damage and crack growth in spot-welded and weld-bonded structures. Preliminary proof-of-concept demonstration tests performed with this method have shown remarkable features and ease of utilization.

1. PRESENT AND FUTURE TRENDS IN JOINING TECHNIQUES FOR AUTOMOTIVE STRUCTURES

The workshop "Basic research needs for vehicles of the future, an integrated perspective of academic, industrial, and government researchers" held at the Princeton Materials Institute, in January 4-6, 1996, under the sponsorship of the National Science Foundation and the Department of Energy in partnership with Chrysler Corporation, Ford Motor, and General Motors Corporation (Anon.,1996) identified light-weight materials as one of the six key areas for future development of vehicle systems. In the light-weight materials area, joining techniques was one of the five focus issues. Besides the continuous use of steel, two additional material classes are being considered for future vehicles: (a) light metals - aluminum and magnesium; and (b) polymer matrix fiber composites. Future joining techniques will have to target these material classes too. Hence, the following joining objectives were outlined:

1. Establish molecular basis for next-generation joining technologies to reduce cost and improve reliability.
2. Improve laser- and resistance-welding of aluminum, magnesium, and their alloys through in situ thermal-profile monitoring and feedback control.
3. Establish surface chemistry effects on weld quality.
4. Extend NDE techniques for welded joints.
5. Develop adhesives to bond metal-to-metal, metal-to-composites, and composite-to-composite surfaces;
6. Study the effect of surface cleanliness on adhesive reliability;
7. Develop NDE techniques for adhesive bonds during manufacturing and in service.

The finding and recommendations of the workshop indicated that welding and adhesive bonding will be the primary low-cost joining methods. In the automotive industry, the welding technique of choice is the resistance welding, with most of the processing being done through the resistance spot-welding variety. This technique is applicable to both steel and aluminum structures.

1.1 Resistance Welding Techniques

The resistance welding processes encompass: spot welding, flash welding, percussion welding, projection welding, resistance seem welding, and others. They all share a common principle: coalescence of the faying surfaces is produced with the heat obtained from the resistance heating of the workpieces as electric current passes between the electrodes simultaneously with pressure being applied through the electrodes.

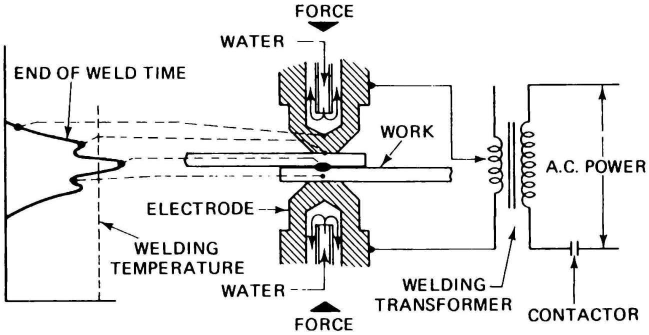

Figure 1 Schematic description of the resistance spot welding technique (Cary, 1994).

The main differences between resistance welding and arc welding are: (a) resistance welding also uses pressure; (b) resistance welding does not use filler electrodes.

1.2 Spot-Welded Structural Types

The type of spot weld currently used in automobile industry are flange joints and top-hat joints. The flange joints (Figure 2) are typical for most car-body joining applications. They can be produced with double access bilateral acting electrodes. The top-hat joints are used in panel reinforcements. If the panel can be properly supported on the other side, the top-hat reinforcements can be applied with one-sided electrode access (Figure 3). This technique eliminates the need for very long electrode arm that can reach across the panel. Double top-hat joints are used in the assembly of structural members (longerons). These members have to sustain significant compressive impact loads during proof testing, and the performance of the spot welded joins is essential. Spot welding has been used with extensive success in the automotive industry in the joining of thin-gage parts made extensively of structural steel.

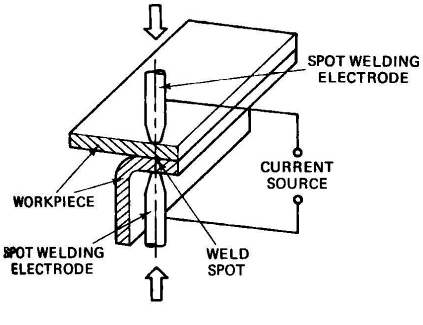

Figure 2 Direct spot welding of flange joints between two opposing electrodes (Cary, 1994).

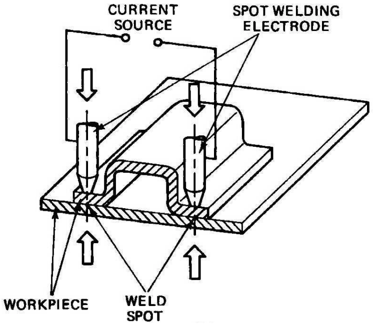

Figure 3 Indirect spot welding of top-hat joints with the electrodes on one side of the work only (Cary, 1994).

1.3 Projection Spot Welding

Another variety of spot welding with significant manufacturing interest is the projection spot welding (Figure 4). In this case, the exact location of the weld is predetermined by the embossment of projections.

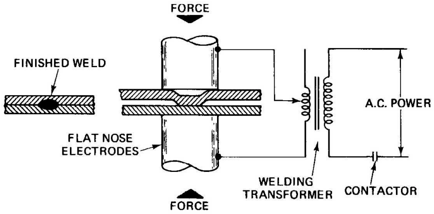

Figure 4 A variant of the spot welding technique - the projection spot welding method (Cary, 1994).

The electrodes used in projection welding are flat-nosed, since the exact location of the weld is not directly controlled by the electrode position. The use of projection spot welding leads to relaxation of positioning tolerances and can create significant cost savings through lowering the defects rate.

1.4 Spot Welding Research Needs

Continuous research is needed to further understand the various material and structural aspects of the welding process and in-service performance of welded parts. The crash strength (impact compression) and fatigue performance of spot welded members continue to present an important challenge. Improved *in-situ* methods are required to monitor weld temperature profiles at part-rates corresponding to automotive manufacturing. Other R&D efforts need to be directed at producing longer-lived weld tips for this process. Modeling is required to establish resistance welding processing windows both for predicting the impact of process-variables on part quality, and for input to sensor-based process-control strategies. Laser welding is another joining option. Here, research challenges include process controls to minimize joint porosity, material loss and plume control during laser welding of complex parts. Non-invasive inspection systems are needed for resistance- and laser-welded parts. Feedback control methods need to be developed for automatic control of optimum processing conditions. According to Rivett (1997), the resistance spot welding is going to be used extensively in the manufacture of steel and aluminum automobile bodies at least for the next decade. Further research is needed to improve the performance and durability of spot welded joints.

1.5 Joining Techniques for Aluminum Vehicular Structures

With the expected replacement of steel with aluminum in vehicular structures, both the welding and adhesive bonding joining techniques are expected to be used. The resistance welding of aluminum is not as well understood as that of steel, and major research challenges are still outstanding regarding the heat generation and heat transfer in the weld-fusion zone.

Adhesive bonding of aluminum structures requires a different set of studies than the welding techniques. Adhesion between the structural substrate and the adhesive material, the fracture toughness of the adhesive layer, and its resistance to crack propagation are among the needed fields of investigation. The advantage of using adhesives is to increase and distribute the transfer of load across the joint, and to increase the structural stiffness of the assembly. The adhesive also acts as filler and sealant.

1.6 Weld-Bonding Technique

A methods that combines the resistance spot-welding welding and adhesive bonding techniques is that of that of weld-bonding. In this technique, adhesion bonding is being considered in combination with spot welding. The result of this process is a new joint type (weld-bond). that is both spot welded and adhesively bonded (Figure 5). Presence of the adhesive ensures load path redundancy. Industrial trials have shown that the use of adhesive in combination with spot welding can bring significant structural benefits such as better load transfer across the joint, increased stiffness, reduced noise, i.e., better overall ride performance.

The adhesive also prevents the bulging of the metal sheets between spot welds during service conditions (Figure 4), and produces effective sealing of the structure. Under certain conditions, fatigue strength improvements may also possible by combining welding with adhesive bonding surrounding the spot-welds.

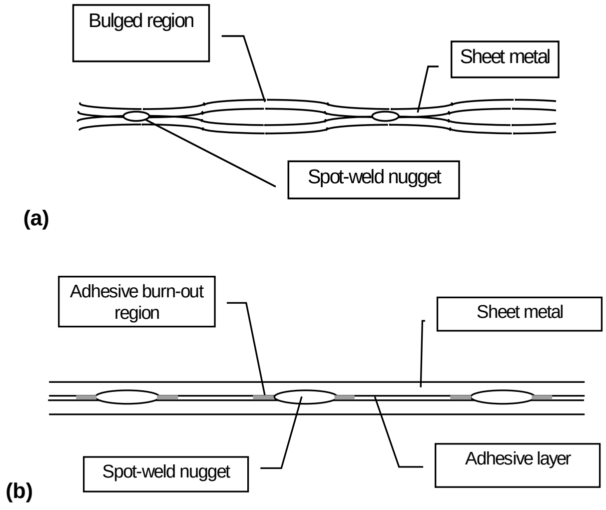

Figure 5 Advantages of combining adhesive bonding and spot welding: (a) without adhesive bonding, the sheet metal may warp and bulge between spot welds due to service loads; (b) with adhesive, warping is eliminated, the joint is sealed, and cracks in the weld nugget are arrested.

However, the scientific basis for determining when and where to use such hybrid weld-bonded joints efficiently and effectively has not been established. This is true for both steel and aluminum spot-welded joints, with the latter posed to gain increased exposure in the years to come

The weldbond process is not entirely matured yet, and various situations may be envisaged: (a) the adhesive is not yet cured during spot welding; (b) the adhesive is partially or totally cured adhesive prior to spot welding; (c) the adhesive is very flexible and behaves like a sealant. A significant aspect of the weldbond process is that a local burn-out and carbonization of the adhesive or sealant will be present close to the spot-welding location. The extend of the burn-out zone depends on the properties of the polymeric material and on the heat flux generated during the welding process. Outside the burn-out zone, the behavior of the polymeric layer will closely resemble that of a conventional adhesion process.

An alternative to the weldbond method is the combination of adhesives and mechanical fasteners. The elimination of the welding process would have significant benefits. However, the mechanical fasteners must be reliable and cost effective. One-sided access fasteners, such as blind rivets, are being considered, but they need an additional drilling operation. More efficient fasteners are sought. A remarkable product is the Henrod fastener (Figure 6) and the equivalent product manufactured by BTM, Inc. Experimental bodies with adhesive plus Henrod fastening may be produced by Chrysler for the Viper model.

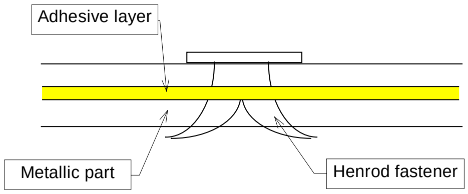

Figure 6 Henrod fastener applied to a pair of adhesively-bonded metal sheets.

For both weld-joints, adhesive-joints, and weld-bond joints, the impact of interfacial chemistry on joint-quality needs further study. Correlations must be established between surface contamination levels (both type and quantity) and joint-strength. Improved non-destructive evaluation (NDE) methods are required for both pre-join contamination levels and post-join mechanical integrity.

1.7 Joining Techniques for Polymer Matrix Composites Vehicular Structures

For polymer matrix composites (PMC) vehicular structures, joining, both through adhesive bond development and mechanical fastening, continues to be a fabrication challenge. Development of material properties and modeling/simulation capability suitable for predicting the performance of PMC structures and components in crash scenarios is the major safety need for widespread use of composites in automotive applications. Finally, design optimization methods have not been developed for PMC in automotive component applications. Such methods would include basic understanding of the role of synthesis and processing on microstructure and subsequently on component performance. Other issues relevant to development of a design methodology include a data base of material properties relevant in automotive service environments, development of repair and maintenance strategies, understanding of damage initiation, propagation and failure mechanisms on the microscale, and development of design tools to optimize the use of the anisotropy inherent in PMC for component fabrication and performance.

2. REVIEW OF NDE TECHNIQUES APPLICABLE TO THE HEALTH MONITORING OF SPOT-WELDED AND WELD-BONDED STRUCTURES

Of the 24 methods for nondestructive evaluation listed by the *ASM Handbook Volume 17 on Nondestructive Evaluation and Quality Control* (Anon. 1992), 18 could be applied, to some degree, for the nondestructive evaluation (NDE) of spot-welded and weld-bonded structures. These are: liquid penetrant inspection; magnetic particle inspection; magnetic field testing; electric current perturbation NDE; magabsorption NDE; electromagnetic techniques for residual stress measurements; eddy current inspection; remote-field eddy-current inspection; microwave inspection; ultrasonic inspection; acoustic emission inspection; radiographic inspection; industrial computer tomography; neutron radiography; optical holography; speckle metrology; acoustical holography; and acoustic microscopy. Additionally, other NDE techniques not listed by the *ASM Handbook Volume 17* may also be used to a certain degree for evaluating the condition of the spot-welded and weld-bonded joints, such as the electric potential measurement, positron annihilation (both mentioned by Shanmugham and Liaw, 1996), dielectric response techniques, and laser ultrasound techniques (Kotidis and Woodroffe, 1995). However, at this stage, it is not entirely clear which of these techniques is most suitable for our particular application, i.e., the detection of incipient damage in spot-welded and weld-bonded structures. It is possible that a more appropriate technique for this application would be one based on the adaptive materials/structures approach, utilizing recent advances in the active materials technology, adaptive algorithms, and smart material systems and structures. Possible candidate techniques based on active materials approach could be based on piezo-electric, piezo-magnetic, or phase-transformation materials. Tagged composites and tagged adhesives approaches have shown some good preliminary results. Of particular interest is the electromechanical (E/M) impedance technique. This technique, still in the experimental stage, has already produced remarkable results for health monitoring and NDE applications.

2.1 The Electro-Mechanical Impedance Technique for Damage Identification

The electro-mechanical impedance technique utilizes the direct and the converse electro-mechanical properties of piezoelectric (PZT) materials, allowing for the simultaneous actuation and sensing of the structural response. The variation of the electro-mechanical impedance of a PZT sensor-actuator interrogator intimately bonded to the structure is monitored over a large frequency spectrum in the high kHz frequency band. Figure 7 presents the experimental set-up for testing the electro-mechanical impedance.

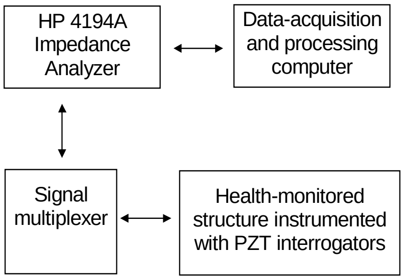

Figure 7 Schematic diagram of the experimental set-up for electro-mechanical impedance testing.

Two basic ingredients are essential of this method: an array of piezo-electric PZT sensor-actuators applied to the monitored structure, and a high-precision impedance analyzer coupled to a data-acquisition computer. The size of the PZT sensor-actuators is typically small (less than 0.5 sq. in., 0.01 in. thick), allowing for non-intrusive installation in the monitored structure. The PZT sensor-actuator is excited electrically by high-frequency low-power voltage. Figure 8 shows the frequency response diagrams obtained during a typical laboratory testing of the electromechanical impedance technique (after Chaudhry *et al.*, 1995a).

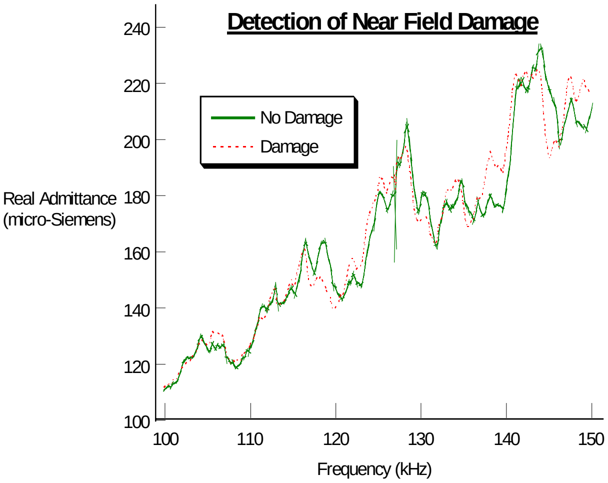

Figure 8 Typical diagram showing the capability of the electro-mechanical impedance technique to detect damage.

The high resolution of this incipient damage detection technique is ensured through the intimate electro-mechanical coupling between the electrical impedance response of the piezo-electric sensor-actuator affixed to the structure and the local mechanical impedance of the adjacent material present in the structure and in the structural joints. Localization of the sensing area ensures sensitivity of the impedance signature only to damage and/or structural changes in the near-field area of the PZT sensor-actuator. The insensitivity of the methods to far-field changes ensures good rejection of the unwanted far-field information and prevents the method from giving “false alarms” due to changes that are part of the normal structural usage (changes in boundary conditions and mass distribution, service loads, etc.)

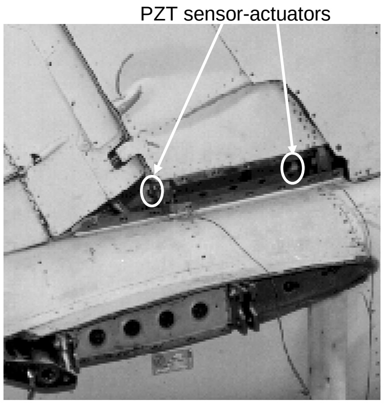

Figure 9 **The electro-mechanical impedance technique used on the bolted junction between the vertical tail and the fuselage of a Piper Model 601P airplane. PZT interrogators were mounted on the fuselage side of the vertical-tail support brackets, each within one inch of the two securing bolts (after Chaudhry *et al.*, 1995a).**

The electro-mechanical impedance technique utilizes well-developed equipment that is currently available for high-frequency accurate measurements of electronic and electro-chemical impedance. This aspect is a significant advantage for quickly bringing this NDE technique to wide-spread practical implementation.

2.2 Exploratory Demonstrations of the Electro-Mechanical Impedance Technique

High-frequency electro-mechanical impedance measurements offer two clear benefits over vibration-based NDE methods: (a) ensures high resolution to incipient material and structural damage; (b) ensures localization of the actuation/sensing area. Chaudhry *et al.* (1995a) used this technique to perform exploratory testing of a typical aircraft joint structure using (Figure 9). The spectral difference between the electro-mechanical impedance curves can be quantified in a scalar value using a least-squares approach, called damage index.

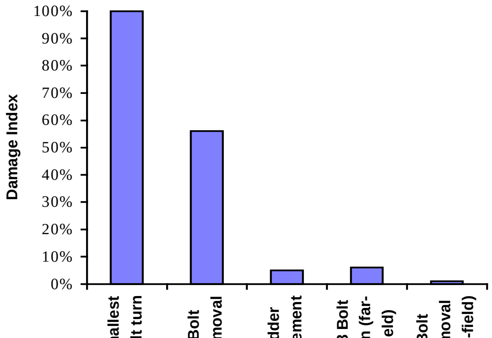

Figure 10 **The damage index bar-chart shows sensitivity to near-field damage and rejection of the far-field changes (after Chaudhry et al., 1995a).**

Figure 10 shows the damage index measured in the exploratory demonstration of the E/M technique performed on the Piper Model 601P aircraft fin/fuselage bolted junction. It is important to notice that the method is highly sensitive to actual damage, while it is relatively insensitive to other types of changes taking place during the normal operation of the aircraft. The sensing localization and sensor cross-talk properties are also remarkably good. Large damage readings were recorded for the smallest bolt turn in the near-field, while almost no reading was obtained when the same change was applied to a bolt in the far field.

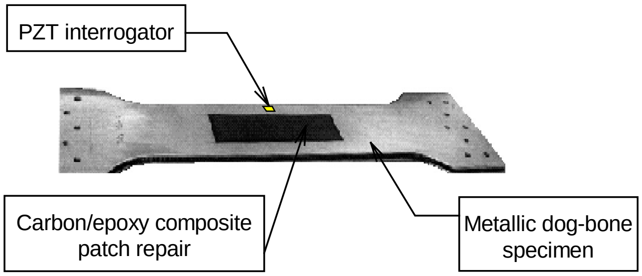

Figure 11 **E/M impedance health monitoring of composite patch repair dog-bone specimen (after Chaudhry *et al.*, 1995).**

Composite repairs of metallic and concrete structures is an area in which adhesive joining techniques are of great importance. Due to in service degradation, a structure can become damaged and develop cracks. Short of complete replacement, the structure can be locally repaired through the application of composite patches consisting of advanced high-strength fibers embedded in a polymeric resin. These composite patches act as crack stoppers. The load field around the repaired crack is redirected through the composite patch. Thus the crack is arrested, and the crack growth is stopped. However, the effectiveness of this commercially attractive process depends to a very large degree on the adhesive bond between the substrate and the composite patch repair. NDE methods for monitoring and early detection of cracks and delaminations in the adhesive interface are essential for the acceptances of this repairs technique.

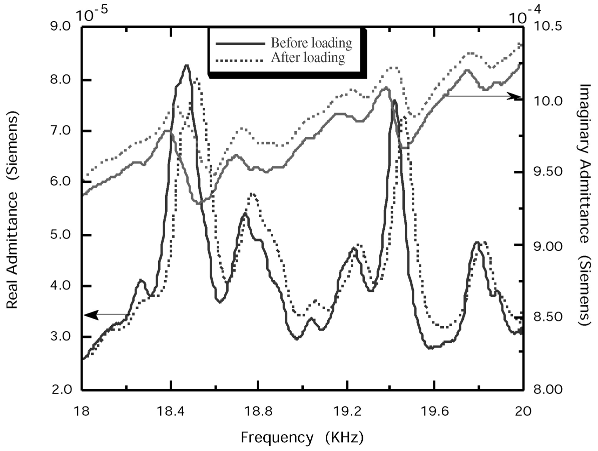

Figure 12 **Changes the real and imaginary parts of the electro-mechanical impedance of the composite repair health monitoring specimen (after Chaudhry *et al.*, 1995b).**

In a typical application, cracks developed in an aircraft metallic skin are repaired with carbon/epoxy patches applied with a wet lay-up technique. To test the applicability of the E/M impedance technique to the repair health monitoring, an experiment was performed using a 700 mm × 126 mm dog-bone specimen repaired with a 200 mm × 70 mm carbon/epoxy patch (Figure 11). A 10 mm × 10 mm PZT interrogator was used to monitor the crack growth under fatigue loading and to detect disbonds in the patch/substrate interface (Chaudhry *et al.*, 1995b). The electro-mechanical impedance measurements (real and imaginary parts) of the monitored specimen before and after fatigue loading are shown in Figure 12.

2.3 Concepts for Using the Electro-Mechanical Impedance Technique for NDE and Health Monitoring of Spot-Welded and Weld-bonded Structures

The newly developed electro-mechanical (E/M) impedance technique is particularly suited for NDE and health monitoring of spot-welded and weld-bonded structures. This novel technique utilizes inexpensive piezo-electric probes that can be permanently affixed to the specimen and interrogated at various time intervals. We propose to use this technique for the evaluation of spot-welded and weld-bonded joints as shown in Figure 13. Since this technique is still under development, it is proposed that its use will be combined with another more conventional NDE technique, and the results be correlated.

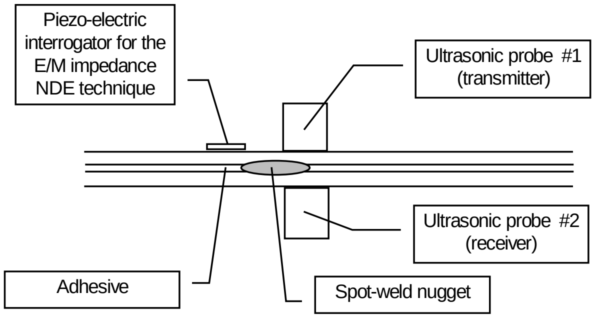

Figure 13 Schematic representation of the proposed NDE technique using the E/M impedance technique and its comparison with conventional ultrasonic NDE.

3. CONCLUSION

A short review of the present and future trends in joining techniques with special emphasis on the automotive industry was presented. Though spot-welding remains an essential technique, the advent of new materials (aluminum and composites) and of new processes (weld-bonding) is posing new challenges to the research community, especially in assessing incipient damage through non-destructive evaluation and health monitoring.

A short review of the existing NDE techniques revealed that many of them may be applicable, to a certain degree, to the health monitoring of spot welded and weld-bonded structures. However, very few such application have been reported, with the exception of X-ray radiography. Novel concepts for health monitoring utilizing an adaptive structures approach are possible. E.g., the electro-mechanical impedance technique utilizes the coupled electro-mechanical response of a piezo-electric interrogators (sensor-actuator crystals) intimately bonded to the monitored structure. An array of such structural interrogators can be envisaged to monitor the incipient local damage and crack growth in spot-welded and weld-bonded structures. Concepts for its laboratory validation on spot-welded and weld-bonded structures were summary explored.

4. ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the National Science Foundation through NSF/EPSCoR Cooperative Agreement No. EPS-9630167.

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