CHARACTERIZATION OF LOW FUSION ALLOYS / METALS WITH EMBEDDED OPTICAL FIBERS

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INTRODUCTION

New materials and structures for advanced aerospace, marine and transportation applications demand the development of sensing and control systems which are capable of optimizing structural properties in response to particular external disturbances. Optical fiber sensors embedded in such structures may be used as life cycle sensors to monitor the way in which the composites and metal structures are fabricated, the in-service lifetime performance conditions of the material, and the onset of material degradation due to a variety of causes including fatigue and impact damage.

Conventional materials that have been considered so far have been graphite-epoxy composites, and extensive research has already been performed on the sensitivity of such sensors vis a vis the orientation of the embedded optical fibers [1,2]. To our knowledge, no work has been reported on the embedding of optical fibers within metals. With the advent of metal-matrix composites (Si-C reinforced aluminum), the need is now being felt to undertake a study of structural health monitoring systems using optical fibers embedded in metals. The first step towards this goal is to characterize metals with embedded fibers.

This paper reports experimental findings on the various methods by which optical fibers can be embedded in metals and their effect on the fidelity of the results. We describe in detail the methods used, the problems encountered, and finally give a comparative table of the acoustic longitudinal velocities and attenuations measured using the different techniques. A theoretical analysis will constitute part of another paper being prepared for presentation in the near future.

EXPERIMENTAL SET-UP

The experimental set-up is shown in Figure 1. The optical subsystem consists of an uncompensated, homodyne, Mach-Zehnder arrangement with a HeNe laser source injecting light into a 4/125 μm fiber. Two 2x2 fused biconical tapered couplers are used for splitting the optical power into the reference and the sensing arms and for recombining the same after the sensing region. An RF gated amplifier was used to power ultrasonic sources operated at 2.25 MHz. Note that the signals obtained with the optical fiber were averaged 1000 times by the digitizing oscilloscope to reduce the effects of "random" low frequency drift in the uncompensated interferometer.

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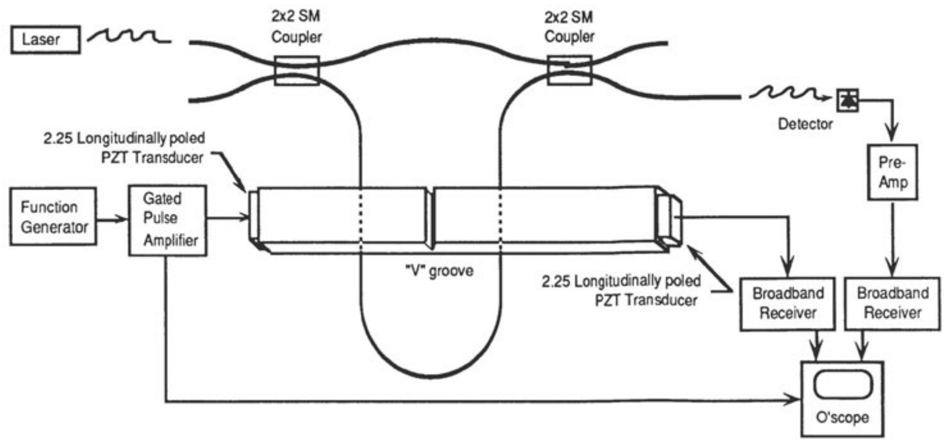

Figure 1. Experimental setup.

OPTICAL FIBERS IN LOW-FUSION ALLOYS

A low-fusion alloy of lead and bismuth (melting point of 255° F) was first considered as the host material because of the relative ease of making molds at low temperatures. Fibers were inserted into molds and the molten alloy was then poured into the molds under a fume hood. Care was taken to ensure that the fiber was kept taut during the pouring process.

Using ultrasonic techniques alone, the longitudinal velocity, attenuation and a sensitivity figure of the PZT transducers were calculated. The results are tabulated in Table 1. The sensitivity figure is a measure of the minimum detectable power at the receiving end of the transducer. The calculation was as follows : The peak input power was 3.67 kW and this source power was reduced until no signal could be detected above the noise floor at the output. For example, attenuating the input by 22.6 dB gave us the minimum detectable signal for an acoustic transducer placed 30.5 cm away. Hence, we denote the sensitivity as 6.89 dB-m. This normalization with respect to length is necessary in order to make a comparison with the sensitivity of the fiber optic sensors which may be placed at various distances. Similarly, for a fiber optic sensor placed 16.3 cm from the source, a reduction of 22 dB gave us the minimum detectable signal. The sensitivity can then be quantified as 3.59 dB-m. Table 1 shows that for a distance 1 meter away from the acoustic source, piezo-electric transducers are more sensitive, which was to be expected because of the inherent sophistication of the ultrasonic techniques. Table 1 also indicates that the measurement of acoustic velocity is quite accurate. However, an excess loss is measured for the attenuation in the system due to the weak coupling between the acoustic signal and the optical fiber.

Table 1. Comparison of acoustic and fiber optic measuring techniques for Pb-Bi bar.

Sensor	Longitudinal velocity	Attenuation	Sensitivity
Ultrasonic PZT transducer	2108 m/s	0.21 dB/cm	6.89 dB-m
Fiber optic Mach-Zehnder	2108 m/s	0.58 dB/cm	3.59 dB-m

EPOXY CHARACTERIZATION

Unlike low-fusion alloys where fibers can be embedded with relative ease, the use of metals with high melting points pose additional difficulties in the embedding process. Although embedding can in principle be done during the manufacturing process, initial laboratory experiments are facilitated with the use of epoxies and other bonding materials to hold fibers within holes in the host metals. As a first step in this direction, we characterize three different epoxies in terms of their acoustic velocity and attenuation in order to gain a better understanding of the mismatch which will be introduced between the host metal and the epoxies.

Epoxies were poured into molds and were cured according to individual specifications. The solid epoxy bars were then used in a measurement scheme depicted in Figure 2, which employs a standard ultrasonic pulsed method for the measurement of acoustic velocity and attenuation. Figure 3 is a plot, which shows the transmitted and received pulses, of the TRA-BOND 2122 epoxy bar using piezo-electric transducers. A description of the epoxies and their properties are summarized in Table 2.

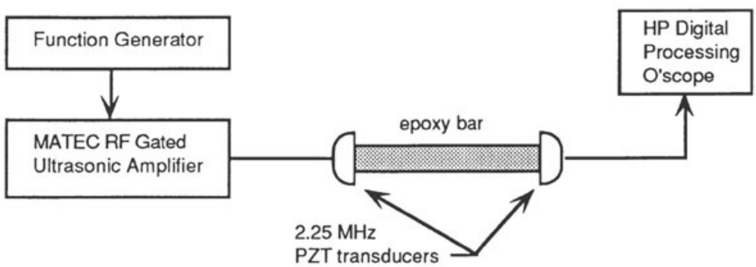

Figure 2. Epoxy characterization schematic

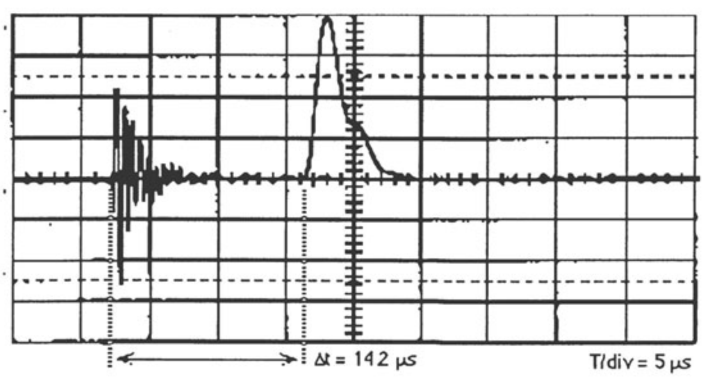

Figure 3. Acoustic transducer plot for epoxy bar characterization.
Figure 3. Acoustic transducer plot for epoxy bar characterization.

OPTICAL FIBERS IN ALUMINUM

Acoustic methods were used to determine the acoustic velocity and attenuation in the 6061 Aluminum bar. Fibers were inserted into holes within the bar and were held in place using each of the three epoxies characterized earlier. A typical fiber sensor output is shown in Figure 4. The three peaked pulse envelope at the right end of the plot is the acoustic receiver response. The two peaks in the center are the outputs from the two interaction regions of the fiber. A comparative tabulation of the results obtained from the different methods is given in Table 3.

Table 2. Epoxy characterization data. All data was taken at 2.25 MHz.

Epoxy Type	Manufacturer	Description	Acoustic Velocity	Attenuation
TRA-BOND 2122	TRA-CON	Aluminum-filled; Cure time: 18 hrs @ 25°C	2564 m/s	5.94 dB/cm
TRA-BOND F113SC	TRA-CON	Low viscosity; Cure time: 18 hrs @ 25°C	2391 m/s	4.2 dB/cm
Epoxy 907 two part adhesive	Miller-Stephenson	Polyamide resin; Cure time: 24 hrs @ 25°C	2125 m/s	9.54 dB/cm

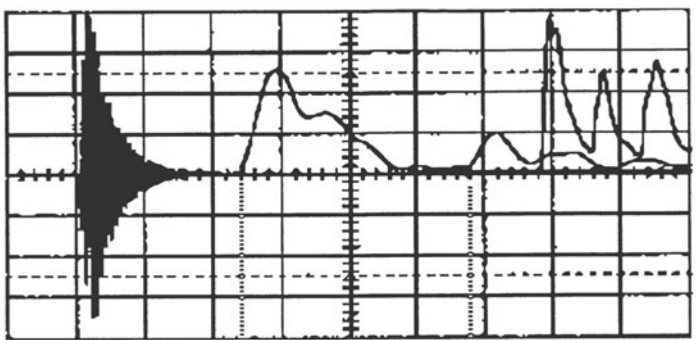

Figure 4. Optical fiber outputs after 1000 averages for the aluminum bar with BA-F113SC epoxy.

Table 3. Comparative tabulation of results.

Sensor	Longitudinal velocity	Attenuation	Sensitivity
Piezoelectric	6129 m/s	0.085 dB/cm	9.36 dB-m
Optical fiber with TRA-BOND 2122	6213 m/s	0.113 dB/cm	3.76 dB-m
Optical fiber with BA-F113SC	6213 m/s	0.189 dB/cm	6.15 dB-m
Optical fiber with Epoxy 907	6213 m/s	0.135 dB/cm	3.87 dB-m

DISCUSSION AND CONCLUSIONS

From Table 3 it is possible to make some preliminary observations about the effect of different kinds of epoxies as the adhering medium. As in the case of low-fusion alloys, the acoustic velocities are measured to a high accuracy, whereas the attenuation measurements are degraded by poor coupling efficiency between the fiber and the medium as well as by correlated (not random) variations in the interferometer Q-point. Since TRA-BOND 2122 is an aluminum powdered epoxy, we would expect it to most accurately replicate the properties of the host metal. This is evident from the 0.11 dB/cm result which is fairly close to the 0.085 dB/cm obtained by using piezo-electric transducers.

Sensitivities of the fiber optic methods are at least 3 dB lower than the piezo-electric transducer techniques. Although this may seem like a disadvantage of the fiber optic sensing method, it is worthwhile to consider some of the advantages of such a scheme:

1) The need for a bulky PZT receiver at the receiving end has been eliminated.
2) The optical fiber can also be used as the transmitting medium for the data obtained from the sensor.
3) Fiber optic sensors, because of their immunity to high temperatures, are more suitable for use in harsh environments.
4) The inherent small size of fibers makes embedding possible with little degradation in host material strength.

Values for the Young's modulus and acoustic velocities as specified by the manufacturer are being obtained. A theoretical analysis is currently being undertaken to systematically interpret these results and will form part of another paper. The v-grooves shown on the metal/alloy bars will be used for possible detection of acoustic emission due to crack propagation once the sensitivity of the fiber-optic acoustic sensor is improved. Methods of sensing such emissions are currently being explored.

In summary, we have presented preliminary results of our work on optical fibers embedded in metals and low-fusion alloys. Longitudinal velocity and attenuation measurements with different techniques have been compared and the feasibility of using similar sensors in future health monitoring systems are being considered.

REFERENCES

1. E. Udd, NASA Workshop on Nondestructive Evaluation, Cocoa Beach, Florida, USA, December 1987.
2. R. M. Measures, Review of Progress in Quantitative NDE, San Diego , California, USA, August 1988.