NONDESTRUCTIVE DEPTH PROFILING OF THE PROTECTIVE COATING ON A TURBINE BLADE

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INTRODUCTION

Turbine blades in an aircraft engine are typically made of a nickel-based alloy, and covered with a protective coating to increase oxidation and hot corrosion resistance. The coating is on the order of 50–100 μm thick. There is currently no nondestructive method available to verify that the blade coating thickness is within specifications, or that the proper interfacial boundary has been set up between the coating and base alloy.

The primary objective of this work is to develop an ultrasonic method for measuring the thickness of the protective coating on a turbine blade from a Pratt & Whitney turbo-prop engine. Secondary objectives include the development of nondestructive methods for depth profiling the aluminum and platinum contained in the coating, and characterizing the amount of interdiffusion at the blade-coating interface. As part of this project, high frequency transducers using a polyvinylidene fluoride (PVDF) element are to be developed for gathering the ultrasonic data.

Two physical principles are to be explored in this work. The first is that the ultrasonic reflection coefficient from an interfacial boundary shows a frequency dependence that is indicative of the interface conditions. By an inversion technique, the echo signal from such an interface can serve as an indicator of its thickness and material profile, as described in [1,2]. The second principle is that the thickness of the protective coating on the blade can be inferred by examining the interference pattern of ultrasonic waves reflected from the two surfaces of the coating.

THEORY

Reflection of Waves at a Diffuse Interface

Consider a compression wave normally incident on a boundary between two media as shown in Figure 1. Assuming a sharp interface between the two media, the reflection coefficient for the wave traveling from material 1 into material 2 is given in terms of the impedance Z by the familiar formula:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{1}$$

If the interface is diffuse, however, as would be the case if there were interdiffusion between the two materials, the reflection coefficient now becomes frequency dependent. Analytical solutions for R do exist for a restricted class of material profiles at the interface [3,4], but in the general case solutions for R can be obtained only by a numerical solution of the one-dimensional wave equation for a non-homogeneous medium:

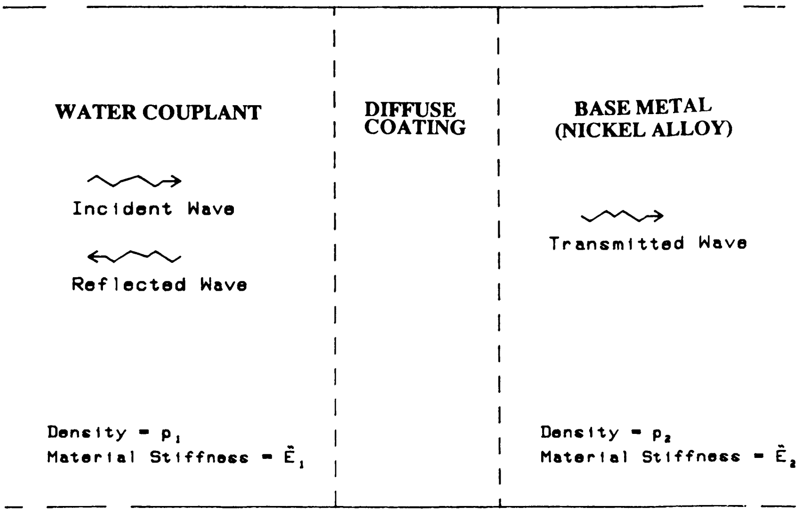


Fig. 1. Compression wave incident on a diffuse interface.

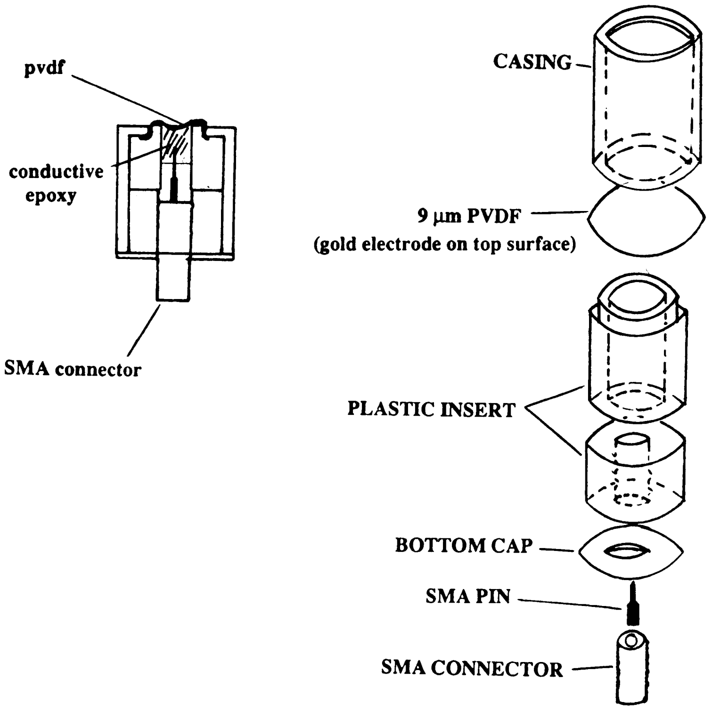


Fig. 2. Assembly drawing for a 50 *MHz* PVDF ultrasonic transducer.

$$\rho(x)\,\frac{\partial^2 u(x,t)}{\partial t^2} = \frac{\partial}{\partial x}\left[\tilde{E}(x)\,\frac{\partial u}{\partial x}\right], \qquad (2)$$

where ρ and $\tilde{E}$ represent particle density and effective material stiffness, respectively, at position x. An algorithm to numerically solve Eq. 2 for particle displacement $u(x,t)$ is presented in [1]. Having solved the wave equation for a particular wave frequency f, the reflection coefficient R from the interface can be calculated. Two characteristics of the solution are noted:

(1) In the case where the interfacial thickness L is far smaller than the sonic wavelength, the interface behaves as a sharp boundary. Clearly no information on the interfacial profile can be obtained under such conditions. It is therefore necessary to ensure that ultrasonic probes of a sufficiently high frequency are used to discern the features of interest.

(2) In the case where the wavelength is much less than L, the reflection coefficient approaches zero. This case is unlikely to arise in the inspection of commercial coatings using conventional ultrasonic equipment.

Thickness Measurements of Thin Layers

The use of ultrasound for thickness measurements is a well-established practice. In cases where the layer thickness is on the same order as the ultrasonic wavelength, however, time-of-flight techniques will not give sufficient accuracy. Instead, the interference pattern set up by multiply-reflected waves from the two surfaces of the protective coating layer can be used to determine the thickness [5].

The technique can be summarized as follows for the case of a thin coating mounted on a high-impedance backing. Provided the coating is an integral number of half-wavelengths thick, the multiply reflected echoes from the coating's two surfaces will all be in phase, resulting in a large total echo signal returned to the probe. By contrast, if the coating is an odd number of quarter wavelengths in thickness, all echoes returned from the coating-backing interface will be 180^o degrees out of phase with the echo from the coating surface.

The experimental data are best displayed by a graph of the reflection coefficient magnitude in the frequency domain. Values of $|R|$ show a series of peaks and troughs as a function of frequency, with a period Δf. The coating thickness can then be calculated as:

$$thickness = ½\,\frac{C_L}{\Delta f} \qquad (3)$$

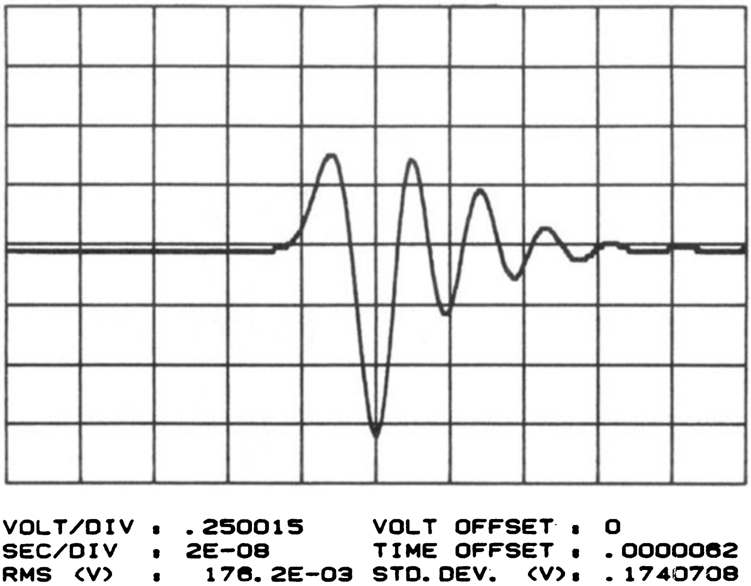
for a longitudinal wave velocity C_L.

EXPERIMENT

High Frequency Transducers

As the blade coatings were known to be on the order of 50 μm thick, with a relatively thin interface between the coating and base metal, it was necessary to use transducers of central frequency 50 – 100 μm to achieve satisfactory resolution. Commercial probes in this range tend to be expensive and of variable quality; therefore probes were manufactured in-house using PVDF of 9-micron thickness as the active element.

The assembly drawing for the transducer is shown in Figure 2. The active element diameter ranged from 3 to 4 *mm* in the prototype probes. The resonant frequency for 9 μm is very close to 50 *MHz*; the echo from a test reflector shown in Figure 3 is consistent with the 50 *MHz* estimate, and illustrates the relatively low damping for this probe design. Experiments are currently underway to increase the signal bandwidth by altering the backing to the active element.



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SEC/DIV  :  2E-08        TIME OFFSET :  .0000062
RMS <V>  :    176.2E-03  STD.DEV. <V>:  .1740708
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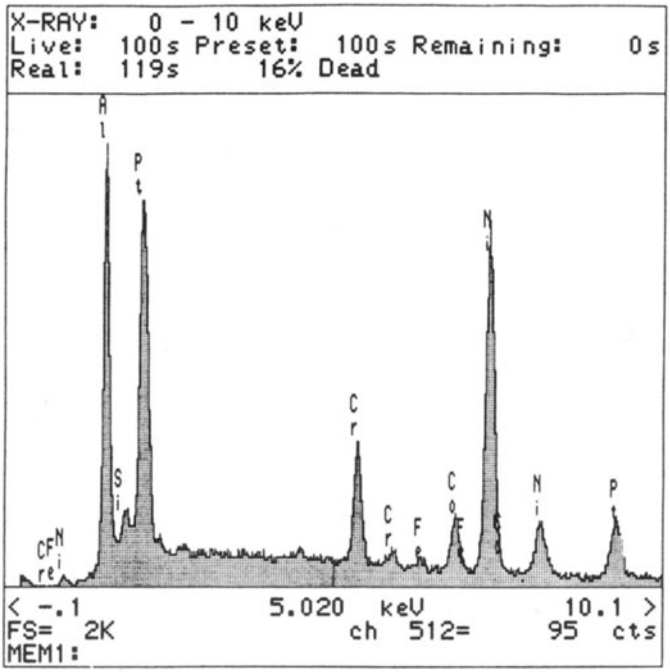
Fig. 3. Echo signal from a reference reflector obtained with a 50 *MHz* PVDF transducer.



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Live:   100s Preset:   100s Remaining:     0s
Real:   119s       16% Dead
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< -.1              5.020  keV          10.1 >
FS=  2K              ch  512=          95  cts
MEM1:
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Fig. 4. Characteristic x-ray lines from turbine blade coating.

Experimental Samples

The turbine blades, Pratt & Whitney part #3111801-01, were made from a nickel-based alloy CPW 363, vacuum melted and cast. The coating was CPW 486 - diffused aluminide with platinum.

One blade was sectioned and placed under a scanning electron microscope (SEM) for destructive analysis of the coating profile. Total coating thickness measured from the outer surface to innermost diffusion zone was approximately 50 μm. Characteristic x-ray lines emitted from the coating surface are shown in Figure 4. As expected, there were strong concentrations of aluminum and platinum from the coating material, plus nickel and various trace elements from the base metal that had interdiffused with the coating. The boundary between the pure base metal and coating material was found to be relatively sharp, with a transition layer only a few microns thick. Testing of additional samples is required to determine whether this profile is typical.

Ultrasonic Measurements

Ultrasonic inspection of the turbine blade was carried out in a pulse-echo immersion configuration, as shown in Figure 5. The signal from the blade surface was gated, digitized, and fed to a microcomputer for storage and analysis. In order to determine the frequency dependence of $|R|$, the echo signals were transferred to the frequency domain using a Fast Fourier Transform (FFT), and deconvolved with the echo spectrum from a reference reflector (a piece of glass).

Preliminary results from one turbine blade are shown in Figure 6 over the range 0–100 MHz; the signal-to-noise ratio was too poor outside this range to obtain significant information. It can be seen that a regular series of peaks and troughs are visible, from which characteristics of the protective coating may be extracted.

RESULTS

The peaks in Figure 6 show a period Δf of approximately 47 MHz. Application of Eq. 3 would then indicate a coating thickness of:

$$thickness = \tfrac{1}{2}\frac{C_L}{\Delta f} = \tfrac{1}{2}\frac{5.5\ mm/\mu s}{47\ MHz} = 59\ \mu m \tag{4}$$

The compression wave velocity of 5.5 $mm/\mu s$ for the coating is only a provisional estimate; an exact measurement of C_L is hampered by the non-homogeneity of the coating and the difficulty in obtaining sufficiently large samples for an accurate measurement. The good correlation between the calculations of Eq. 4 and the SEM analysis indicates the estimate of sonic velocity to be accurate to within about 20%.

Information on the depth profile of the individual coating constituents cannot be readily obtained from Figure 6. The relative sharpness of the peaks and valleys of this graph, however, do indicate the interfacial layer between coating and base metal to be much smaller than the sonic wavelength, which was on the order of 100 μm at 50 MHz. Clearly, an ultrasonic system operating in the hundreds of megahertz or even higher would be needed to have the resolving power to see the interfacial details.

SUMMARY AND CONCLUSIONS

Preliminary tests have been conducted to measure the thickness of the protective coating on a turbine blade using ultrasonic compression waves. Calculations of the coating thickness as given by Eq. 4 agree to within about 20% of destructive analysis results with a SEM. The major source of error is believed to be the speed of compression waves in coating material. Further samples are required to determine the reliability and repeatability of the technique.

The distinctive interference pattern obtained by ultrasonic waves reverberating inside the coating indicates that the diffusion zone between the coating and base metal is relatively thin. Under such circumstances, it is not anticipated that any information on the diffusion profile will be obtained using 50 MHz waves.

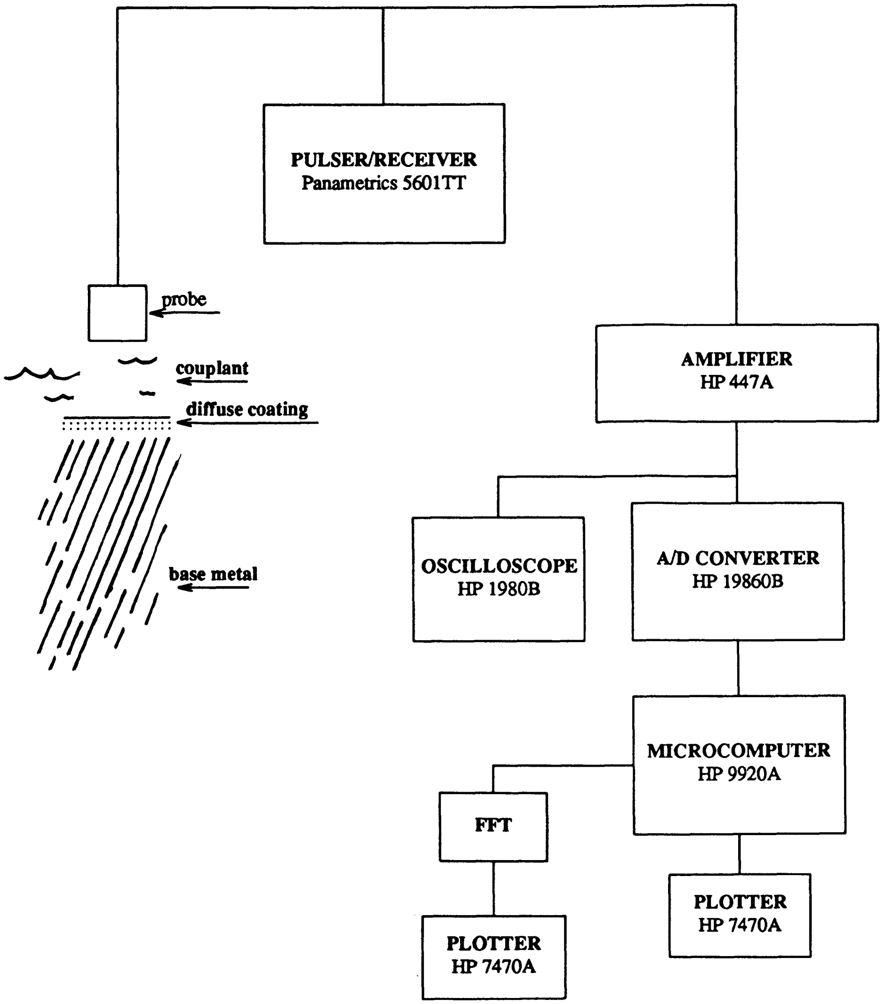

Fig. 5. Pulse-echo immersion test configuration.

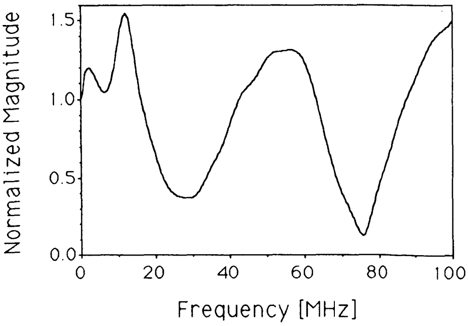

Fig. 6. Deconvolved echo signal from turbine blade surface.

A technique to manufacture 50 *MHz* ultrasonic probes using a PVDF active element was developed. The cost per probe, including all materials and labour, is under $100. Further work is required in developing suitable backing for the PVDF to minimize resonant ringing. Work is also underway to construct probes using a more efficient piezoelectric than the PVDF.

Several major challenges remain in the development of a system to measure the protective coating thickness:

(1) The coating profile is highly complex; each element has its individual diffusion characteristics and shows a different depth profile in the SEM.

(2) The coating is sufficiently thin that high frequency ultrasonics must be used. This brings the added complications of weak signals, poor signal-to-noise ratio, and the need for careful impedance matching of the components in the testing system.

(3) The physical properties of the coating (E, ν, ρ), as a function of nickel, aluminum, and platinum concentrations, are not precisely known.

(4) Signal processing poses a special difficulty. Because there are so many unknown parameters related to the coating profile, no simple mathematical algorithm can solve this inverse problem. A more realistic objective under such conditions would be to solve for one or two key parameters such as coating thickness and average nickel-to-aluminum atom ratio, while assuming other parameters do not greatly deviate from a reference state.

ACKNOWLEDGEMENTS

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