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Oblique Ultrasonic Backscatter for Detecting Corrosion at Metal-Rubber Interfaces

15 August 1995

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An ultrasonic technique for detecting corrosion at metal-rubber interfaces is introduced. The technique, which bears resemblance to the angle beam techniques commonly used in weld inspections, is based on the principle that corrosion pits will backscatter a small percentage of obliquely incident sound. Preliminary data from the study of isolated, artificially induced pits on an aluminum surface are presented. Isolated pits with dimensions on the order of 50 µm are readily detected on the surface of bulk aluminum plates using 10-MHz pulses injected into the plate through a face perpendicular to the surface. Two successful applications of the technique within the aerospace industry are discussed. The first application involves inspection for corrosion in an aluminum-rubber bondline. The second application is to the inspection of a D6AC steel, O-ring sealing surface.

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1. Introduction

Within the aerospace industry, inspections of metal-rubber interfaces are often performed ultrasonically. Unfortunately, minor corrosion-induced surface changes that can weaken a metal-rubber bondline or prevent the sealing of an O-ring do not lead to a significant change in a normally reflected signal. An alternate approach is to monitor the backscattered signal from pulses that strike the interface obliquely, as depicted in Figure 1. In this instance, most of the acoustic energy is forwardscattered so as not to compete with the relatively small backscattered signal from small surface changes. Such an approach is very similar to the angle beam techniques commonly used in the inspection of welds. Preliminary results from the study of the backscatter from isolated pits similar to those found grouped on corroded surfaces are presented in the next section. Often what drives the development of a new technique also prompts its application before the nuances associated with its basic principles can be fully studied. Such was the case here. Two applications of the technique discussed above to the recent inspection of flight hardware are described in the third and fourth sections of this report. In both of these applications, the presence of detrimental corrosion could be successfully discriminated from the nominal surface finish of the metal; however, improvements in the technique, particularly in the area of signal processing for feature extraction, could be envisioned.

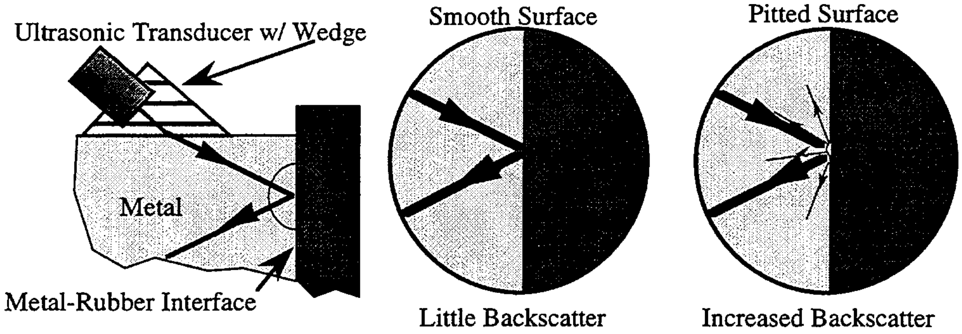

Figure 1. Surface pitting can be detected by monitoring the amplitude of the backscatter of sound transmitted at oblique incidence to the surface.

2. Backscatter from Isolated Pits

2.1 Sample Preparation

To study oblique reflection from isolated pits, a 100 × 50 × 25 mm, 7075-T6 aluminum block was prepared. The 50 × 25 mm faces of this block were polished using 360 grit sandpaper. Pits were then created on these faces using one of two methods. The first method involved using a Rockwell hardness tester with a 1/16-in.-diameter ball. The loading on the ball could be adjusted to change the pit depth. Application of the hardness tester (HT) produced small, crater-like impressions with raised edges. The raised edges were removed by repolishing the face of the block, leaving somewhat smooth spherical indentations as can be observed in the top left micrograph of Figure 2. The approximate diameter and depth of the pit in this micrograph is indicated in the figure. Other pits were created using an electro-discharge machine (EDM). This process was harder to control, with the shape, diameter, and depth of the pit being significantly affected by both the shape of the discharge tip and the length of the discharge. A representative EDM pit micrograph is presented in the top right of Figure 2.

2.2 Apparatus

The aluminum block was suspended in a water-filled immersion tank opposite a 10-MHz, 1/4-in., unfocused Krautkramer-Bransen, Model 113-126-420 immersion transducer, as depicted in Figure 3. A Panametrics Epoch II, Model 2100 flaw detector was used in pulse-echo mode to both stimulate the transducer and to receive reflected pulses. The aluminum block was attached to a rotational stage, which, in turn, was attached to two orthogonal translational stages. The two stages were oriented so as to permit vertical and horizontal movement of the block while maintaining the angle between the block face and the transducer. A rotational stage setting of $\phi = 0°$ put both faces parallel. The distance between the transducer face and the opposing surface of the aluminum block was adjusted to ~70 mm to keep the end of the transducer near field in the water.

2.3 Experiment

For a selected pit, the block was adjusted vertically so that the height of the pit was coincident with that of the transducer center. The rotational stage was then adjusted to $\phi = 23.3°$ so that longitudinal pulses emitted by the transducer would mode-convert at the water-aluminum boundary to produce shear pulses striking the pitted surface at $\theta = 34°$ to its normal. The horizontal translational stage was then adjusted to maximize the backscattered signal from the pit, and its amplitude was recorded. The measurement was repeated with $19° \leq \phi \leq 27°$ corresponding to $18° \leq \theta \leq 47°$.

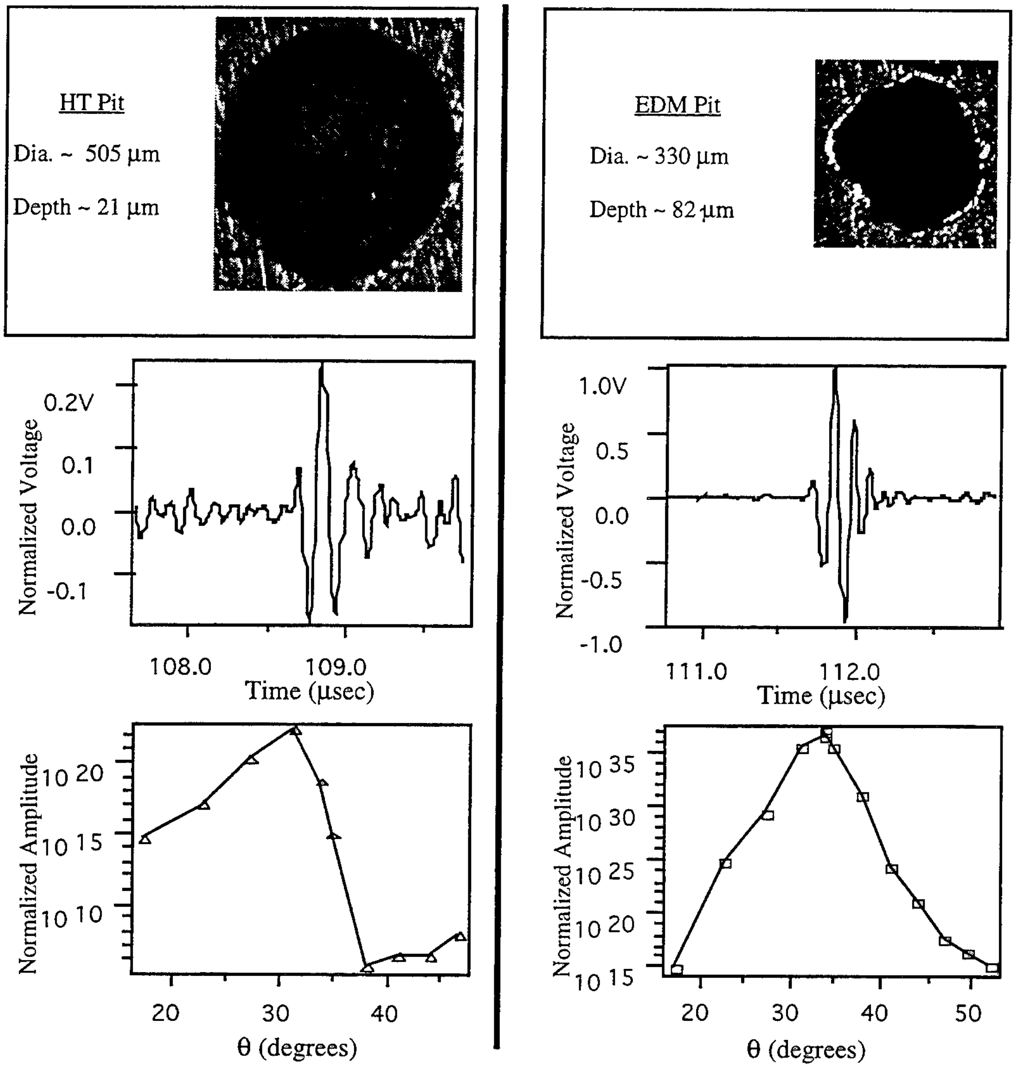

Figure 2. Representative micrographs of a pit in aluminum created using a hardness tester (top left) and an EDM (top right). The backscatter waveform at $\theta = 34°$ and the signal amplitude as a function of θ for each pit are displayed below the respective micrograph.

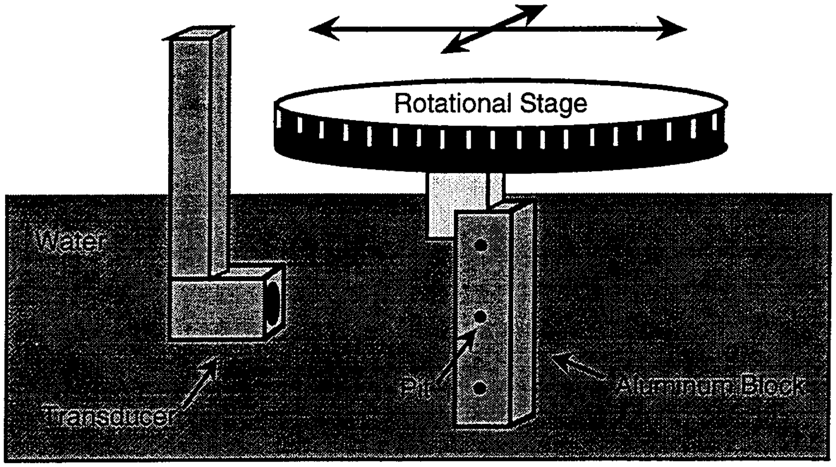

Figure 3. Apparatus used to measure ultrasonic backscatter from pits.

2.4 Results

Producing pits of a repeatable nature proved more difficult than might be expected. Even if the size and shape of two pits appeared relatively equivalent, the way in which they scattered sound (amplitude and angular dependence) was often surprisingly different. The results presented in Figure 2 are a fair representation for the majority of the pits studied. The backscatter waveform at $\theta = 34°$ from the pit depicted in each micrograph of Figure 2 is shown as an example beneath the micrograph. The input pulse was of the same amplitude in both instances. The smaller diameter but deeper EDM pit gave rise to a larger signal. It can be observed that for both pits the signal is easily distinguished from the noise floor. The data accumulated thus far suggest that individual pits having dimensions on the order of 50 µm (~2 mils) on the surface of polished 7075-T6 aluminum give rise to signals easily discerned with the current apparatus. (For reference, the wavelength for 10-MHz shear waves in aluminum is ~310 µm). It should be noted that for other grades of aluminum, such as the lower-strength alloy 6061-T6, similar measurements become much more difficult because the noise floor is much higher. The bottom plots in Figure 2 represent the signal amplitude as a function of θ for each pit. It should be noted that the ordinate in each plot is logarithmic. As one would expect, the results reveal that for a contact inspection the choice of wedge angle is crucial. In this instance, maximum sensitivity to the pits occurred for $\theta \sim 34°$.

3. Application 1—Bondline Corrosion

The oblique backscatter technique was used to solve a difficult Solid Rocket Motor (SRM) inspection problem. These SRMs represent a significant capital investment. Concern had been raised regarding the integrity of SRMs for which the storage time had exceeded the original qualification period. The concern was heightened when potentially detrimental corrosion was detected in an aged scrapped motor case that was sectioned and analyzed as part of the re-qualification effort. The SRMs of interest consist of a composite case lined with a rubber insulator. The solid propellant is cast in the space between the insulator and a center mandrel. Removal of the mandrel leaves an open center bore. The poles (ends) of the composite case, adjacent to the bore, are terminated with forged, 7175-T736 alloy, aluminum bosses. The corrosion was observed to occur at the interface (in the bondline) between the rubber insulation and the polar boss as depicted in Figure 4. Significant corrosion in this region of a flight motor could (1) provide for a leak path behind the insulation, resulting in a case burn, or (2) weaken the bondline, allowing it to unzip upon ignition. Either of these phenomena could lead to catastrophic failure.

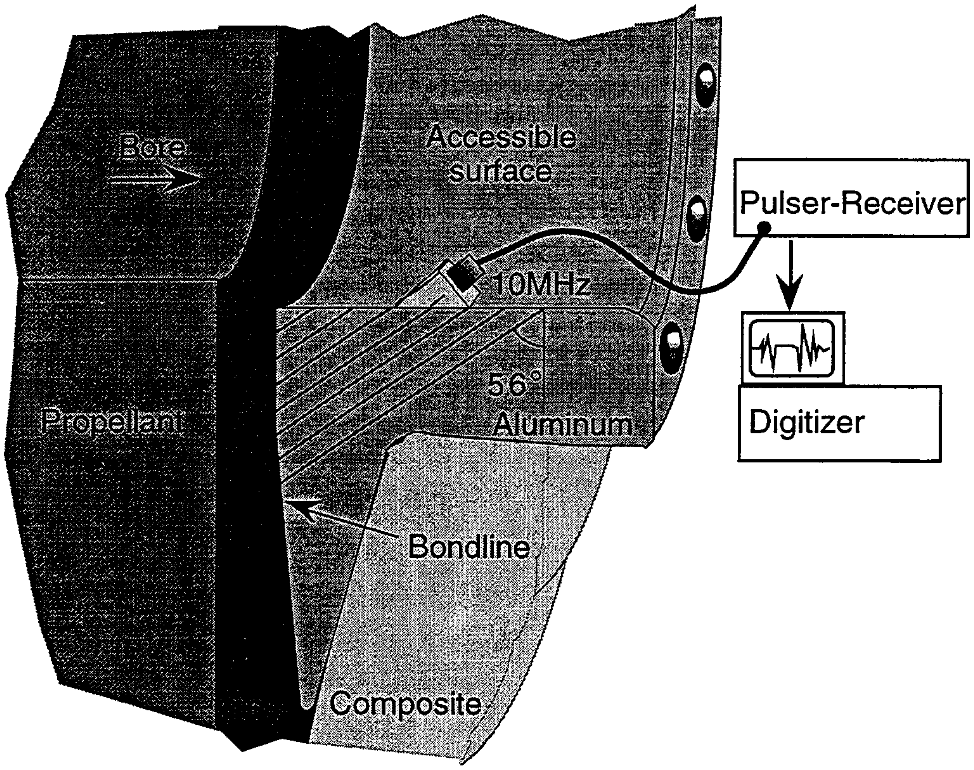

Figure 4. SRM aft polar region sectional view. The bondline indicated was inspected for corrosion by scanning the transducer on the inner radius of the aluminum polar boss as shown.

The search for an appropriate nondestructive means for detecting corrosion in the polar boss-insulation bondline prompted the suggestion by M. C. Gregory of United Technologies Chemical Systems Division to use an oblique, ultrasonic backscatter technique for which he provided the initial proof-of-concept testing data. Further development of the technique proceeded with recommendations and assistance from J. M. Nelson and R. L. Carlson of Boeing and two of this report's authors (ECJ and JRL). The nominal surface condition for the polar boss at the interface consisted of a 250–500 microinch grit blast finish. Close observation of this finish revealed that pits with dimensions on the order 1–2 mils could be found. Corrosion deemed reportable was shown to result in a backscatter amplitude four times that due to the nominal condition.

Analysis indicated that inspection of the first 1.8 in. of the bondline measured radially from the bore (360° around) would be sufficient. To perform the inspection, a 10-MHz, Krautkramer Bransen, Model 113-226-590, 1/4-in.-diameter transducer with a 60° (in steel) shear wedge was manually scanned along the accessible inner surface of the polar boss (a surface that is perpendicular to the bondline) as shown in Figure 4. Application of Snell's law reveals that pulses emitted by the transducer strike the bondline at ~34°, resulting in a healthy reflection from surface anomalies (compare with Figure 2). In a standard scan, the signal was measured at seven positions along the first 1.8 in. of the bondline for each degree, resulting in a 7 × 360 point grid. The placement of the transducer on this grid was controlled using a notched T-square that mated with notches on the side of the transducer wedge. The RF signal measured at each grid point was digitally recorded for post-processing. Because the signal path through the boss increased with radial distance from the bore, a sliding gate and distance amplitude correction (DAC) were used to process the data.

A 45° segment of a sample C-scan plot of processed data from one of the inspections is presented in Figure 5a. Each pixel represents one data point. The color bar is normalized so that the shade corresponding to unity represents the nominal surface condition. In Figure 5b, the same data is interpolated to a finer grid to aid in visualization of patterns. This data set is of interest because signals were detected that exceeded the reporting threshold of four times that of the nominal surface condition. To better evaluate the affected region, it was scanned a second time on a much finer grid. This information together with the results of a bondline load test led to the conclusion that the corrosion-like indications did not coalesce to form a continuous leak path or a region of sufficient size and proximity to the bond edge so as to seriously compromise the bondline.

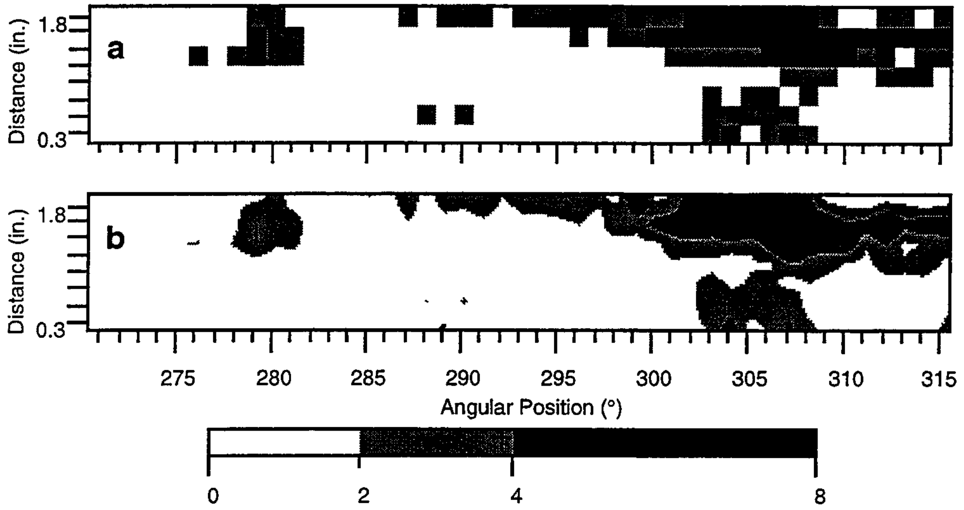

Figure 5. Sample C-scan data from a SRM bondline inspection. The shade of each pixel in (a) corresponds to the amplitude of the signal captured at the associated angular and radial position. The color bar has been normalized so that unity corresponds to the nominal (250–500 microinch) surface condition. Signals greater than unity generally correspond to a rougher surface condition at the bondline. The threshold for reporting and further evaluation was set at four times the nominal condition. In (b) the data from (a) is interpolated to a finer grid to bring out the patterns.

4. Application 2—O-Ring Sealing Surface Corrosion

The oblique backscatter technique for corrosion detection was also used to solve a second SRM inspection problem. In this instance, the SRMs of interest are much larger than those discussed above. To facilitate transportation and handling, these SRMs comprise a number of cylindrical segments. The segments are "stacked" at the launch base, and a pair of the resulting SRM boosters are mated to a core vehicle. The outer wall of the segments are made of D6AC steel. The joint between segments consists of a tang and clevis, as depicted in Figure 6. This figure presents a sectional view of one side of the cylindrical case joint. In the actual launch configuration, the tang points upward. The segments are secured to each other by a series of pins; the outline of one is evident in the figure. An O-ring is employed to seal the joint. A leak in this O-ring seal could lead to a catastrophic failure.

Special precautions are taken to ensure that the O-ring sealing surface is free of corrosion. However, because of the aggressive climatic conditions at coastal launch sites, even with precautions, corrosion-related concerns are raised if schedule delays result in a SRM having an unusually long tenure on the launch pad. Unfortunately, a visual inspection of the O-ring sealing surface would require destacking the segments, a costly proposition that would significantly impact the launch schedule. To solve this problem, M. C. Gregory examined the geometrical constraints associated with the joint and designed special wedges that permit interrogation of the O-ring sealing surface with sound of oblique incidence (Figure 6). Defect standards were manufactured, and it was shown that isolated 2-mil-deep EDM pits could be detected on the O-ring sealing surface. The technique has since been adopted as routine procedure, with a baseline scan performed when the segments are first stacked, followed by periodic checks as the vehicle awaits launch.

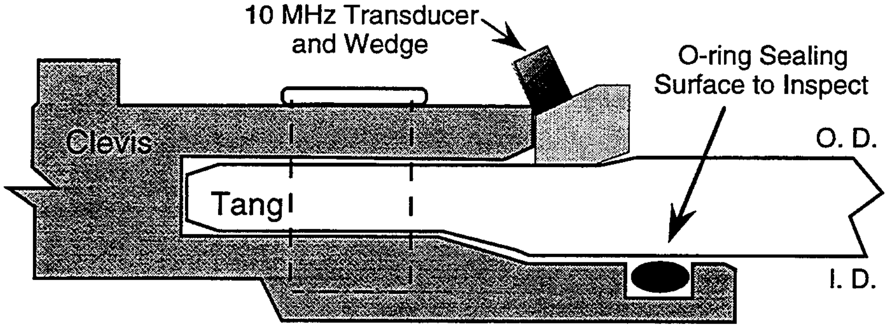

Figure 6. Schematic of joint between SRM segments. To inspect the O-ring sealing surface for corrosion visually would require a costly destack of the entire SRM. Instead, an oblique-incidence ultrasonic backscatter inspection is performed using a transducer and wedge as shown.

5. Discussion

Corrosion at metal-rubber interfaces can be detected using ultrasound propagated at oblique incidence to the interface. Indeed, two successful examples of such work are reported herein. The technique is relatively easy to implement, being quite similar to the shear wave techniques commonly used for weld inspection. However, the applicability of the technique is limited by both the bulk and surface quality of the metal. While the basic principle behind the technique is easy to understand, wave scattering from rough (corroded) surfaces can be quite complex.* To determine ways in which the basic technique can be improved, studies involving the simpler case of scattering from isolated pits have been initiated. The results presented here are, to say the least, quite preliminary. Initial difficulties were encountered in trying to produce pits with repeatable characteristics. Future work will be directed toward determining just how much information can be gleaned from backscattered signals. The effects of pit size, shape, density and distribution, signal frequency, and incidence angle should be measured and compared with models. This information will be used to develop signal processing algorithms that would enable one to better discriminate between different types of metal-rubber interface anomalies such as machine marks, scratches, disbonds, pitting, etc.

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* Ogilvy, J. A., *Theory of Wave Scattering from Random Rough Surfaces*, Institute of Physics Publishing Ltd., Bristol and Philadelphia (1991).

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