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ULTRASONIC EVALUATION OF A JOINT BETWEEN
ALUMINUM AND STAINLESS STEEL MADE BY
ELECTROPLATING NICKEL AT THE INTER-
SECTION OF THE TWO METALS

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UNION
CARBIDE

OAK RIDGE Y-12 PLANT
OAK RIDGE, TENNESSEE

*prepared for the U.S. ATOMIC ENERGY COMMISSION
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ABSTRACT

An ultrasonic test has been developed to detect the presence of unbonded areas in nickel-stainless steel and nickel-aluminum electroplated joints. A through-transmission technique using a threshold C-scan output is used to locate the defective areas. Since ultrasonics is insensitive to the strength of adhesion, a proof test is required to delaminate weakly bonded areas and is made in conjunction with the ultrasonic test. Data have been obtained which show the correlation between the indicated and actual flaw sizes.

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SUMMARY

An ultrasonic test has been developed to determine the area of bonding between the aluminum-to-nickel and Type AM-363 stainless-to-nickel joints of an electroplated bond. A through-transmission technique using a threshold C-scan output was determined to be best suited for indicating any areas of no adhesion that might be present. Since ultrasonics is not sensitive to weak adhesion, a proof test is made to delaminate any weak areas that might be present. Correlation between C-scan indications and actual flaw sizes was made by the metallographic sectioning of coupons.

INTRODUCTION

A joint between aluminum and Type AM-363 stainless steel requires an evaluation of the area that is well bonded.

The edges of these two parts are tapered and these tapered edges are placed together to form a V-shaped groove. Nickel is electroplated in this groove and adheres to the exposed surfaces to form a strong bond between dissimilar metals. Because of its functional use, this joint must withstand high stress levels. Unfortunately, nondestructive testing methods are not presently capable of evaluating the strength of joints and bonds. In this joint, nondestructive testing can only locate areas with a complete lack of adhesion. Consequently, it is necessary to have a proof test. To proof test a part, one end is placed in a hot, fluidized sand bed while the other end is restrained by a steel and thermoplastic ring—producing stress in the bond. This stress was calculated to be equivalent to the design stress for the bond. After the proof test is performed, the ultrasonic inspection then determines whether any delaminations have occurred.

This report describes the development of a test at the Oak Ridge Y-12 Plant^(a) to detect unbonded areas. An initial procedure was used on a number of parts and found to have numerous problems, namely: extraneous indications such as interference bands, lack of correlation between the actual and detected flaw size, and nonrepeatability of the test. This original test consisted of a through-transmission technique using 15-MHz lithium sulfate transducers and a black-white, C-scan output scanned at various thresholds. A lack of standards and the presence of tapered areas in the bond combined to make it nearly impossible to reproduce results from one setup to another. These problems led to a renewed effort to improve the test and related procedures. This report describes a number of experiments that were designed to reduce or eliminate the previous difficulties that were encountered.

(a) Operated for the US Atomic Energy Commission by the Union Carbide Corporation's Nuclear Division.

EVALUATING THE BOND

TEST MATERIALS

The bond is composed of a Type AM-363 stainless steel ring and an aluminum (Type 6061-T6) ring, both of which are tapered. These rings are clamped with their thin edges just touching, and the tapered area is filled by drawing electroplating nickel. Extra material is then machined to the proper tolerances. A drawing of the finished joint is provided in Figure 1. For proper adhesion it is necessary to first electroplate a thin layer of copper (copper strike) to both surfaces. With no copper strike, the bond is weak; but, since ultrasonics is not sensitive to bond strength or the presence of monolayers, it cannot detect this absence of the copper strike. This fact is mentioned here because of the difficulty encountered in producing known size defects (unbonds). Most of the methods used to produce recognizable defects involved leaving out or removing the copper strike. Because these bonds still had some strength, ultrasonics could not detect these defects. However, once these weak bonds were stressed sufficiently to break them (as they would be in the proof test), they were readily detected by ultrasonics.

Figure 1. A PART BOND AND THE ULTRASONIC THROUGH-TRANSMISSION TECHNIQUE USED TO INSPECT IT.

ULTRASONIC THEORY

Ultrasonics is commonly used as a nondestructive testing tool to inspect joints for flaws. In the case of this bond, ultrasound is transmitted into the bond; and, by detecting either the relative transmission or reflection of ultrasonic energy from the interface in the joint, unbonded areas can be located. Detection of the lack of adhesion at an interface can be accomplished using several different techniques. The pulse-echo technique would "see" a considerably larger reflection at an unbonded interface than for a bonded interface, while a through-transmission technique would detect an unbonded area by the reduced transmission through an unbonded interface. Theoretically, it can be shown that, due to the impedance mismatch introduced by the free surface caused by a lack of adhesion, most of the energy is reflected from an unbonded area while only a portion is reflected from an interface that is actually bonded together. When the ultrasonic pulse reaches a bonded interface, the amount of energy transmitted or reflected depends upon the acoustic impedance of the materials on either side of the interface. The transmitted and reflected sound pressure coefficients take the form:

$$P_t (1,2) = \frac{2Z_2}{Z_1 + Z_2}, \text{ and} \quad (1)$$

$$P_r (1,2) = \frac{Z_2 - Z_1}{Z_1 + Z_2}, \quad (2)$$

where Z_1 and Z_2 represent the acoustic impedances of Media 1 and 2. The acoustic impedance is defined as the product of the density and longitudinal velocity of the medium. Table 1 lists the densities, longitudinal velocities, and acoustic impedances of the materials used.

Table 1
PERTINENT MATERIAL PROPERTIES

Material	Density (gms/cc)	Longitudinal Velocity (cm/sec $\times 10^5$)	Acoustic Impedance (gms/cm ² $\times 10^6$)
Aluminum	2.70	6.40	1.73
Type AM-363 Stainless Steel	7.75	5.87	4.55
Nickel	8.90	5.48	4.85

Using Equations 1 and 2, a transmitted amplitude of approximately 53 percent would be expected from a well-bonded area of nickel plated onto the aluminum, and a reflected amplitude of approximately 47 percent would be obtained from the same area; whereas, the transmitted amplitude would be essentially zero in an area with no adhesion, while the reflected amplitude would be one. In addition to this analysis it was shown experimentally that the pulse-echo method and the delta-scan technique were less sensitive than the through-transmission technique.

Interference phenomena due to multiple reflections of the interface complicate the data interpretation because a decrease in the transmitted amplitude is obtained when the ultrasonic beam crosses an area of no adhesion. However, when the thickness of a sample under ultrasonic inspection is of the same order of magnitude as the wavelength of the sound being used, destructive interference which could give a signal indistinguishable from that of an unbonded area can be expected. The wavelength of sound at 10 MHz is 25 mils in aluminum, 23 mils in Type AM-363 stainless steel, and 22 mils in nickel; and, since the thicknesses of the bond materials vary from 0 to 0.10 inch, interference was expected and was a substantial factor in the development of a workable test. When the thickness is an even multiple of a half wavelength, constructive interference takes place; when the thickness is an odd multiple of a half wavelength, destructive interference is seen. With the original test, interference bands were common and difficult to distinguish from actual flaws. To help distinguish interference bands from flaws, a halftone scan was put into use. A halftone scan writes gradations of gray for a preset span of amplitudes. For this particular case the halftone writes black for a signal greater than 80 percent, white for signals less than 55 percent, and varying shades of gray for signals between 55 and 80 percent. The signal-level percentage refers to the percentage of a full-scale signal

on the cathode ray tube display of the ultrasonic flaw detector system. The particular choice of 80 percent for full signal was made as a matter of convenience and convention. An interference will be indicated by a graded band, usually around the entire circumference; on the other hand, a flaw will have a discrete gray level on a halftone scan.

TRANSDUCERS

Lithium sulfate 15-MHz transducers were first used because of their sensitivity and availability. These particular transducers were replaced by 10-MHz highly damped ceramic transducers to eliminate or reduce the number of interference bands. A major problem with the lithium sulfate transducers was the appearance of a large number of interference bands in the edge section of the bond area where the aluminum or stainless steel became very thin. This phenomenon is particularly troublesome at the edge because of the likelihood that these feather edges would actually be unbonded. It was determined that lower frequencies would prove to be even better, but the spatial resolution was reduced due to the lower frequency. Ten-MHz transducers were picked as the best compromise between resolution and interference effects. A second reason for the use of 10-MHz ceramic transducers is that they are active transducers and will yield a wave shape that is nearly independent of the type damping, whereas lithium sulfate transducers are passive and depend on the type of damping. Since the interference phenomenon depends on the frequency content (pulse shape) of the pulse and the ceramic transducers have a constant pulse shape, their use eliminates another variable. It should be noted that the pulser/receiver should be tuned for minimum pulse width and thus maximum resolution. This adjustment was indicated by an improved definition on C scans of flaws scanned using various settings of pulser/receiver tuning.

Figures 2 through 6 provide representative photographs of transmitted waveforms used in the bond study. In all photographs, the horizontal axis represents time (0.2 microsecond per division) and the vertical axis represents the amplitude in millivolts (50 mv/div for Figure 2, 10 mv/div for Figures 3 and 5, and 5 mv/div for Figures 4 and 6). Figure 2 is a photograph of a waveform transmitted through water by a 10-MHz focused ceramic transducer and received by a 10-MHz flat ceramic transducer. The ringing effect is due to improper impedance matching between the receiving transducer and the oscilloscope amplifier. Figure 3 is a photograph of the same waveform transmitted through a well-bonded area on an electroplated nickel/aluminum coupon, while Figure 4 is a photograph of the waveform transmitted through an unbonded area of the same coupon. There is an order-of-magnitude difference in signal amplitude between the signal transmitted through water alone and that transmitted through the coupon. The signal is further reduced by a factor of three in the unbonded area of this coupon. An internal reflection due to an impedance mismatch between materials is most probably responsible for the difference in the waveshape seen in Figures 2 and 3. Figures 5 and 6 are again the same waveform transmitted through bonded and unbonded areas of an electroplated nickel/stainless steel coupon, respectively. Note here that the transmitted waveform through the well-bonded nickel/stainless area is essentially the same as that transmitted through water alone.

Figure 2. RF WAVEFORM TRANSMITTED THROUGH WATER. (Wave Transmitted by a 10-MHz Focused Ceramic Transducer and Received by a 10-MHz Flat, Ceramic Transducer)

Figure 3. RF WAVEFORM TRANSMITTED AT 10-MHz THROUGH A WELL-BONDED AREA OF AN ELECTROPLATED NICKEL/ALUMINUM COUPON.

It was shown that there is no significant difference between the transmission directions for the bond. The transmission coefficients were calculated using the formula: (b)

(b) *Ultrasonic Testing of Materials*, Krautkramer Springer-Virley, Inc, New York (1969).

$$D_{I/I} = \frac{2\rho_2 c_2 |c_{2t} c_{1t}| \cos^2 2a_{2t} \cos 2a_{1t}}{\rho_1 c_{1t} \cos 2a_{1t} \sin a_{1t} N},$$

where:

Figure 4. RF WAVEFORM TRANSMITTED AT 10-MHz THROUGH AN UNBONDED AREA OF AN ELECTROPLATED NICKEL/ALUMINUM COUPON.

Figure 5. RF WAVEFORM TRANSMITTED AT 10-MHz THROUGH A WELL-BONDED AREA OF AN ELECTROPLATED NICKEL/STAINLESS STEEL COUPON.

Figure 6. RF WAVEFORM TRANSMITTED AT 10-MHz THROUGH AN UNBONDED AREA OF AN ELECTROPLATED NICKEL/STAINLESS STEEL COUPON.

$$N = 2\cot a_{1t} + \frac{c_{1l}}{2c_{1t}} \frac{\cos^2 2a_{1t}}{\cos a_{1l}} + \frac{2\rho_2 c_{2t}^4}{\rho_1 c_{1t}^4} \cot a_{2t} + \frac{\rho_2 c_{1l} c_{2t}^3}{2\rho_1 c_{1t}^4} \frac{\cos^2 2a_{2t}}{\cos a_{1l}},$$

$D_{l/l}$ represents the transmission coefficient,

$\rho_2 c_{2l}$ the impedance (Medium 2),

c_{2t} the shear velocity (Medium 2),

c_{1t} the shear velocity (Medium 1),

c_{1l} the longitudinal velocity (Medium 1),

a_{1t} the angle of reflection (shear wave, Medium 1),

a_{2t} the angle of refraction (shear wave, Medium 2),

a_{1l} the angle of incidence,

ρ_1 the density of Medium 1, and

ρ_2 the density of Medium 2.

The transmission coefficients for the composites were:

Ni/SS	Ni/Al
$D_1 = 0.116$ from the Ni side	$D_2 = 0.159$ from the Al side
$D_1^1 = 0.107$ from the SS side	$D_2^1 = 0.163$ from the Ni side

Since there is less than ten percent difference in coefficients, the direction of inspection is trivial. Calculations indicate that the Ni/Al signal level should be 3 db larger than the Ni/SS signal level. Experimentally, the difference was found to vary between 2 to 4 db. Thus, for ease of alignment, the transmitter is placed on the inside and perpendicular to the part axis since the outside surface is at an angle to the axis while the inside is parallel to the axis. This setup is illustrated in Figure 1.

A flat receiver was chosen because it was determined that a slight beam offset would affect the response less than if a focused transducer had been used as a receiver. It also was indicated by improved flaw resolution on C scans that the receiver should be placed in the far field zone rather than the near zone. A distance in the far field zone of 2.5 inches from the part was chosen to eliminate another setup variable (focusing transducers).

THRESHOLDS

One of the most important aspects of the inspection development was the introduction of a fixed threshold 30 percent below that signal level transmitted through a good bond region (ie, any area which transmits a signal whose amplitude is 30 percent below that through a good area is called an unbonded area). This difference between the transmitted signal and threshold will give a one-to-one correspondence between an actual flaw size and detected flaw size. The need to determine a threshold can be seen by referring to Figures 7 and 8. Figure 7 is an analog scan of a flawed coupon; Figure 8 is a single analog pass showing various threshold levels and size indications corresponding to these threshold settings. From Figure 8 it can be seen that, for a black-white C scan which writes white below a preset threshold level, the area of white indication depends strongly on the level of the threshold setting. For example, as the threshold is lowered from T_1 to T_2 the apparent area of unbond decreases from S_1 to S_3 . The point on the flawed area at which the C scan indicates a flaw moves as the threshold is varied. This point moves because the signal from the flaw varies relatively slowly rather than

Figure 7. AN ANALOG SCAN OF A NICKEL/ALUMINUM UNBOND. (Note Slopes of the Walls)

Figure 8. DIAGRAM SHOWING WHY THE SIZE OF A C-SCAN INDICATION VARIES WHEN THE THRESHOLD IS CHANGED.

abruptly at the edge of the flaw. This phenomenon is illustrated clearly in Figure 9 where, as the threshold varies, the size indication of the flaw varies drastically. Figure 9 shows two flaws, one 5/8 inch in diameter and the other 1/2 inch in diameter. As the threshold is lowered from 70 to 20 percent, the apparent flaw size decreases. Only the 55 percent threshold setting has shown these flaws in their true size. The threshold is varied to determine the correct setting to give a one-to-one correspondence between the indicated and actual flaw size. For 80 percent transmission, a threshold set at 55 percent

Figure 9. C SCAN OF A NICKEL-ALUMINUM COUPON WITH THE SIGNAL SET FOR 80 PERCENT TRANSMISSION THROUGH WELL-BONDED MATERIAL.

gives the desired indication. A number of both Ni/SS and Ni/Al coupons, and a section of a quarter-scale part, were scanned at the 50 percent level threshold and then metallographically sectioned to determine the actual flaw size. Results of this comparison appear in Table 2. These data indicate an average difference of approximately 20 mils. With a transducer spot size of 50 mils, this difference is acceptable. Thus, a threshold located 30 percent below the signal from a good bond produces a good correlation between the indicated and actual flaw size on both Ni/SS and Ni/Al bonds. Figures 10 and 11 are black-white C scans of samples used in the metallographic study to determine the correlation for a threshold setting that is 30 percent below the signal level for a good bond. Figure 10 is a scan of two Ni/Al coupons with 3/4, 3/8, 1/2, and 1/4-inch-diameter flaws. Several of the areas prepared had some

Figure 10. C SCAN OF TWO NICKEL/ALUMINUM COUPONS WITH THE GOOD BOND TRANSMISSION SET AT 80 PERCENT AND THE THRESHOLD SET AT 55 PERCENT.

adhesion. Coupon (b) was sectioned while Coupon (a) was saved for possible use as a standard. Figure 11 is a scan of a section of a quarter-scale part (B4-16) and shows only the Ni/SS and SS portions of the bond. The four unbonded areas were cut and their widths measured to compare with the indications shown on this C scan. Results are summarized in Table 2. Typical photographs of an unbonded interface between nickel and aluminum can be seen in Figures 12 and 13 and of the blend point between the Ni/Al and Ni/SS regions in Figure 14. These

Table 2
CORRELATION BETWEEN ACTUAL AND
DETECTED FLAW SIZE

Bond Type	Flaw Number	Design Size (inch)	C Scan (inch)	Metallographic Size (inch)
Ni/Al	1B	0.750	0.78	0.771
Ni/Al	2BA	0.625	0.63	0.579
Ni/Al	2BB	0.500	0.49	0.428
Ni/Al	3B	0.625	0.60	0.591
Ni/SS	1F	0.875	0.86	0.843
Ni/SS	2F	0.625	0.70	0.662
Ni/SS	3F	0.500	0.50	0.499
Ni/SS	4F	0.250	None	None
Ni/SS	B4-16-1	Unknown	0.21	0.225
Ni/SS	B4-16-2	Unknown	0.17	0.142
Ni/SS	B4-16-3	Unknown	0.08	0.095
Ni/SS	B4-16-4	Unknown	0.02	0.051

photographs were used in the study to determine the unbond sizes metallographically. Notice in Figure 12 the discontinuity of the point where the copper flash ends. This condition is characteristic of all these coupons and may be due to the surface preparation.

One point that should be made clear with respect to standards is that unless the standard has the same ultrasound attenuation characteristics as the part to be inspected it is

Figure 11. A BLACK-WHITE C SCAN OF A QUARTER-SCALE PART SHOWING INDICATIONS OF UNBONDS IN THE NICKEL/TYPE AM 383 STAINLESS STEEL AREA OF THE BOND. (Section of Part B4 16)

impossible to set levels through the standard and have correlatable data on the part. Remembering that the correlation depends on the 30 percent signal change, the signal change and consequently the correlation is only maintained if the standard and part transmit sound with equal attenuation. To demonstrate the truth of these statements, a concept of a bond or part fingerprint can be defined. The part fingerprint is an analog scan across the bond perpendicular to the circumferential direction. Examples of a part fingerprint are presented in Figures 15 and 16. These fingerprints are both taken from the same part at different locations. There are only minor differences between them. On the other hand, fingerprints of different parts, appearing in Figures 17 through 19, are considerably different from each other. A fingerprint also contains information on the relative transmission levels in Al, Ni/Al, Ni/SS, and SS. A fingerprint is a useful tool to make comparisons of transmission characteristics between one part and another. Comparison of a part before and after proof test can be made from Figures 15 and 18. Since no standard was available to adjust the setup to the same conditions both before and after a proof test, a level comparison was impossible; but the test did show a change in the fingerprint design, indicating some effect due to the heat treatment caused by the proof test.

ALIGNMENT PARAMETERS

Transducer setup parameters including offset, angle, and spacing were varied to determine their effect on resolution and their optimum settings. Transducer offset or misalignment was tested to determine what variation in signal amplitude it could introduce. The setup used is seen in Figure 20. A representative plot of signal amplitude versus transducer position is given in Figure 21. Misalignment can affect the signal amplitude as much as 15 percent; however, if the alignment variations are held to within 50 mils, amplitude changes are not significant. The receiver was held fixed while the transmitter was scanned over the sample coupon and the receiver. The sensitivity of the setup to transmitter angulation was also investigated. Here, the transmitter was angulated over the sample coupon with the receiver in a fixed position behind the coupon, as in Figure 22. Figure 23 points out the variation in signal as a function of the angle to the normal. As long as the angle is within $\pm$ three degrees of normal, the effect is negligible (5 percent signal change). Transducer spacing was investigated by moving the receiver from the near field to the far field zone and observing the resolution of flaws on a C scan. Placement in the far field zone gave the best resolution.

Figure 12. PHOTOGRAPH OF THE BEGINNING OF AN UNBOND BETWEEN NICKEL AND ALUMINUM.

Figure 13. PHOTOGRAPH OF THE SAME UNBOND AS IN FIGURE 12, BUT IN THE CENTER AT ITS GREATEST WIDTH.

Figure 14. PHOTOGRAPH OF THE BLEND POINT BETWEEN ALUMINUM, NICKEL, AND TYPE AM-363 STAINLESS STEEL.

Figure 15. FINGERPRINT OF PART 0002 AT ZERO DEGREES AFTER A PROOF TEST.

Figure 16. FINGERPRINT OF PART 0002 AT 90 DEGREES AFTER A PROOF TEST.

SCANNING METHODS

Since the amplitude is different in the Ni/Al and Ni/SS bond areas, it is necessary to change the instrument gain when scanning these areas to compensate for this change. The order of scanning the bond area is not particularly important, but what is important is that, whatever order is chosen, should be the one that introduces no uncertainties at the blend point. Initially, the instrument attenuation was adjusted as the scan crossed the blend point, but lack of certainty with respect to the position of the blend point

Figure 17. FINGERPRINT OF A REJECTED PART AT ZERO DEGREES BEFORE THE PROOF TEST.

Figure 18. FINGERPRINT OF PART 0002 AT ZERO DEGREES BEFORE THE PROOF TEST.

Figure 19. FINGERPRINT OF PART 1955 AT ZERO DEGREES BEFORE THE PROOF TEST.

Figure 20. SETUP FOR TESTING THE EFFECT OF MISALIGNMENT ON THE RECEIVED AMPLITUDE.

Figure 21. ANALOG RESPONSE OF A FIXED RECEIVER TO A TRANSMITTER SCANNED ACROSS THE SAMPLE.

Figure 22. SETUP FOR TESTING THE ANGULATION EFFECT ON AMPLITUDE.

Figure 23. ANALOG RESPONSE OF A RECEIVER AS THE TRANSMITTER IS ANGULATED ABOVE THE SAMPLE. (Scale Is 1.15°/Major Division)

(especially when the scan is in progress) produced uncertainties in the bond condition at the blend point. Thus, the Ni/Al and Ni/SS areas should be scanned separately. Markers should be used to indicate the boundaries.

RECOMMENDATIONS AND CONCLUSIONS

Some comments are offered here on the results of the development effort to design a test that will reliably detect unbonds and display their size accurately. To maintain a correlation between the detected and actual flaw sizes, an amplitude difference of 30 percent between a good bond signal and the threshold setting must be maintained. Since there were no production parts to measure the variations in transmission characteristics, it is difficult to establish the reliability of using a standard to set the signal levels. The standard will not necessarily transmit ultrasound the same as the part being inspected. This aspect of the inspection procedure will be defined when the parts become available. The repeatability of the test depends on the consistency of the setup. A good method to test a setup for consistency is with a standard or reference part. With the present data it is recommended that the standard be used to check the setup and not to set levels of transmission. It should be mentioned again that ultrasonics does not detect weak bonds or areas devoid of the copper strike, but is capable of detecting small unbonds that are approximately 50 mils in diameter.

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