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Ultrasonic Evaluation of Dissimilar-Metal Transition Joint Welds

J. H. Smith

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ULTRASONIC EVALUATION OF DISSIMILAR-METAL TRANSITION JOINT WELDS

J. H. Smith

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CONTENTS

ABSTRACT 1
INTRODUCTION 1
DESCRIPTION OF TRANSITION JOINTS AND DISCUSSION OF PROBLEM 2
ACOUSTICAL PROPERTIES 5
TEST PARAMETERS 10
Weld Test Samples 10
Testing Techniques 12
Test Equipment 13
Scanning Techniques 14
Gating and Distance-Amplitude Corrections 15
WELD NOISE LEVEL AND SIGNAL-TO-NOISE RATIO 17
DISCUSSION OF TEST RESULTS 18
Weld Interface of 2¼ Cr-1 Mo and ERNiCr-3 18
Weld Interface of Type 316 Stainless Steel and 16-8-2 Weld Metal 31
Weld Interfaces with Alloy 800 35
Alloy 800/16-8-2 Weld Interface 36
Alloy 800/ERNiCr-3 Weld Interface 40
CONCLUSIONS AND RECOMMENDATIONS 42
ACKNOWLEDGMENTS 43

ULTRASONIC EVALUATION OF DISSIMILAR-METAL TRANSITION JOINT WELDS[1]

J. H. Smith

ABSTRACT

We have studied ultrasonic techniques for the nondestructive examination of the dissimilar-metal transition joints designed for the Clinch River Breeder Reactor. This included determining the acoustical properties of the various materials involved and evaluating the relative merits of several examination techniques and associated parameters. Using the results of these studies we developed ultrasonic inspection methods that can be used to evaluate 12.7- and 25.4-mm-thick dissimilar-metal welds in transition joints in the as-manufactured (machined) condition. We can routinely detect with a 2:1 signal-to-noise ratio notches whose depths are 8% of the weld thickness at any of the four weld root interfaces and in the weld root volume of both welds. Better sensitivity can be obtained if multiple test frequencies are used and if only the root areas of the welds and weld interfaces are considered.

INTRODUCTION

Dissimilar-metal transition joints are relatively common in fossil-fired steam plants and in nuclear reactor systems. Components such as superheaters, headers, and certain piping that must function at higher operating temperatures are constructed of austenitic stainless steels. The primary boilers and heat exchangers operate at relatively lower temperatures and can be constructed of ferritic steels. Transition joints are necessary to tie these systems together. These dissimilar-metal transition joints are usually in the form of pipe welds with outside diameters varying from 75 to 750 mm and with thicknesses ranging from around 5 to 25 mm.

Historically, dissimilar-metal transition joints have functioned satisfactorily,[2] but failures have occurred in fossil plants, and the potentially serious nature of a failure in a nuclear system makes the requirement of a valid nondestructive evaluation quite significant. Transition joint welds are generally made in the form of spool pieces, which are later installed in the operating system. These spool pieces are available for inspection in the as-manufactured condition before installation. At this time both weld surfaces are accessible, and the inspection can usually be performed in a controlled area under normal operating conditions.

As-manufactured inspections are beneficial, but it is desirable and necessary to examine pipe welds after they have been installed in the reactor. Only the outside surface of the pipe (crown surface of the weld) is accessible for this in-service inspection, and the test must be performed in a relatively hostile environment, with surface temperatures reaching 250°C and a background radiation level up to 5 R/h (0.36 μA/kg). At present visual methods are the only code-acceptable techniques that can be used to perform in-service inspections on stainless steel reactor pipe welds. Radiography is used to inspect these welds in the as-manufactured condition, but is not applicable for in-service inspection. Ultrasonic methods are presently being used to evaluate the condition of in-situ pipe welds on a best effort basis, but there is no universally accepted procedure for performing these tests.

The ultrasonic inspection of ferritic steel welds is difficult, but conforming test techniques have been established. Austenitic stainless steel welds present a greater problem; they severely attenuate ultrasound,

[1] Work performed under DOE/RRT 189a OH103, "Piping and Fittings Development."

[2] J. F. King, *Behavior and Properties of Welded Transition Joints Between Austenitic Stainless Steel and Ferritic Steel – A Literature Review*, ORNL-TM-5163, 1975.

and high noise levels generated within these welds can mask true indications. In addition, isolated noise signals sometimes cannot be distinguished from actual defect indications. The problem then becomes one of signal-to-noise ratio and the interpretation of test results. There may be several contributing factors, such as precipitates and microfissures, but it is generally accepted that most of the difficulties that occur with the ultrasonic inspection of these welds can be associated with the coarse dendritic structure, which is characteristic of austenitic stainless steel welds. Several recently published reports[3–5] describe how acoustical properties can vary in an austenitic weld depending on the mode of vibration and the direction of propagation of sound energy with respect to the cellular dendritic structure in the given weld.

This report describes how the solution to a particular weld examination problem was obtained. The results are general and may apply to many other similar test situations.

DESCRIPTION OF TRANSITION JOINTS AND DISCUSSION OF PROBLEM

The Clinch River Breeder Reactor (CRBR) dissimilar-metal transition joint (DMTJ) (Fig. 1) involves three base metals and two weld metals. The 2¼ Cr-1 Mo ferritic steel is joined to type 316 stainless steel through an intermediate metal, alloy 800. Alloy 800 is used to smooth out the large change in coefficient of thermal expansion (CTE) between 2¼ Cr-1 Mo and type 316 stainless steels. The type 316 stainless steel and alloy 800 used in this study were both high-carbon alloys. The "H" designation is omitted throughout this report for convenience. The two weld metals [ERNiCr-3 (Inconel 82) and 16-8-2 stainless steel], both of which are nickel-chromium alloys, were chosen for their welding characteristics and to maintain a smooth CTE gradient. A hot-wire gas tungsten-arc welding technique was used for both welds. The weld joint parameters shown in Fig. 1(b) are typical except for the larger than normal root opening, which was chosen to help reduce stresses in the weld zone. The diameters of transition joint pipes are 76, 152, 457,

[3] B. L. Baikie et al., "Ultrasonic Inspection of Austenitic Welds," *J. Br. Nucl. Energy Soc. 15*(3):257–61 (1976).

[4] B. R. Dewey, L. Adler, R. T. King, and K. V. Cook, "Measurements of Anisotropic Elastic Constants of Type 308 Stainless-Steel Electroslag Welds," *Exp. Mech. 17*(11):420–26 (November 1977).

[5] D. S. Kupperman and K. J. Reimann, *Ultrasonic Wave-Propagation Characteristics and Polarization Effects in Stainless Steel Weld Metal,* ANL-78-29 (March 1978).

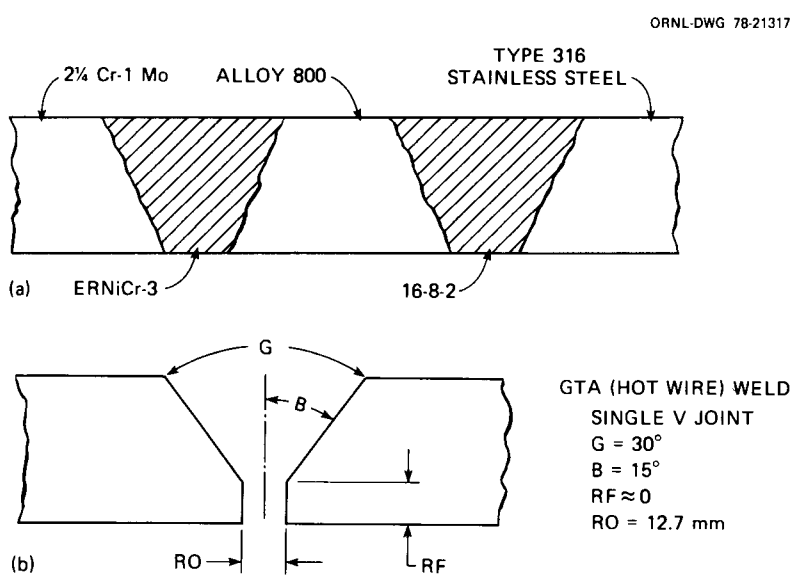


Fig. 1. CRBR dissimilar-metal transition joints. (a) Materials. (b) Joint geometry.

and 660 mm, and corresponding thicknesses are 5.5, 7.1, 12.7, and 25.4 mm. Our efforts were concentrated on the 12.7 and 25.4 mm weld thicknesses.

Figure 2 shows cross-sectional views of the two transition joint welds. Figure 3 shows typical grain structures for the three base metals. Grain patterns and sizes can significantly affect the ability to ultrasonically inspect materials. These effects will be discussed in more detail later in this report.

The CRBR transition joint presents two welds and four weld interfaces to be ultrasonically inspected, each possessing slightly different acoustical properties. Our original problem was to develop an ultrasonic inspection procedure that would be capable of detecting cracks in the weld and cracks and lack of side wall

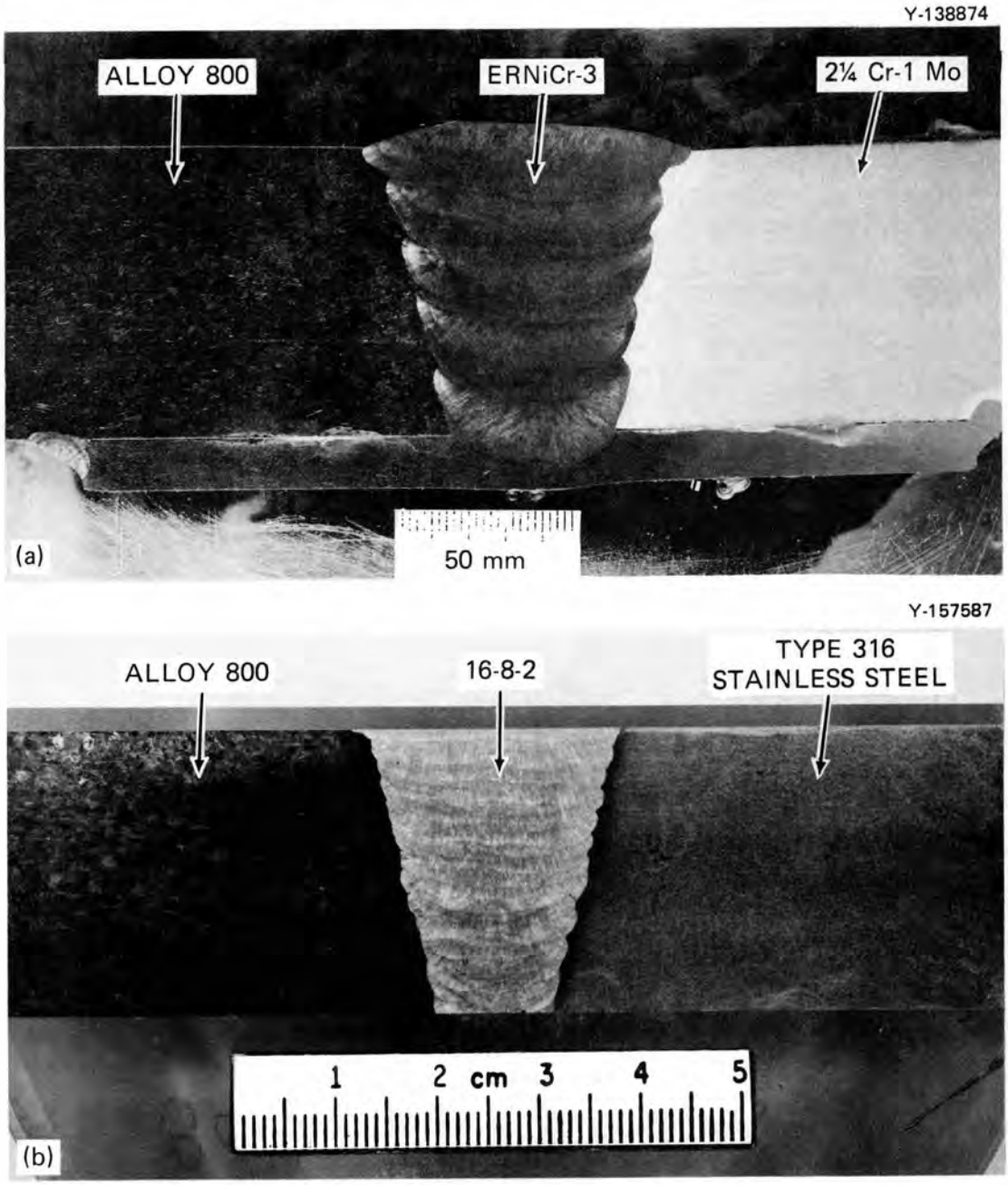


Fig. 2. Cross sections of CRBR transition joints. (a) 13-mm-thick ERNiCr-3 weld (b) 29-mm-thick 16-8-2 weld.

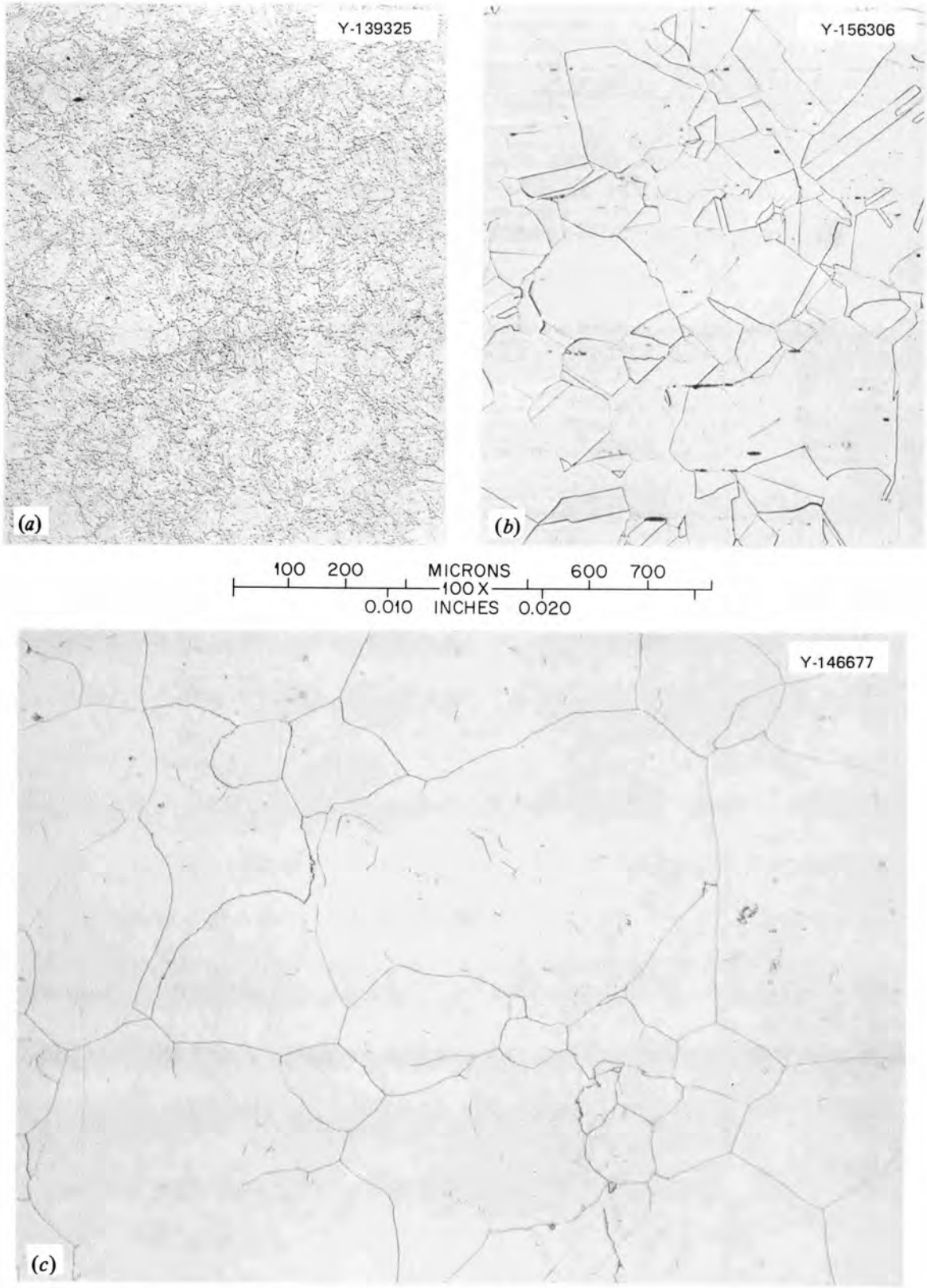


Fig. 3. Grain structure of transition joint base metals. (a) 2¼ Cr-1 Mo. (b) Type 316 stainless steel. (c) Alloy 800.

fusion at the weld interfaces. In addition, we were requested to emphasize the ability to detect cracks in the base metal adjacent to the fusion line at the interface between 2¼ Cr-1 Mo steel and ERNiCr-3 weld metal.

ACOUSTICAL PROPERTIES

Our first approach to solving this problem was to examine the basic acoustical properties of the materials involved. Longitudinal and shear velocity measurements were made in the three base metals and two weld metals, and the average values are shown in Table 1. Small cubical samples were machined out of the welds for the velocity measurements in weld metal, and shear cut crystals were used for the shear velocity measurements. The longitudinal and shear velocity data shown in Table 1 were determined for sound propagating in the crown-to-root direction in the weld samples. During these velocity measurements we noted a polarization effect for shear velocity; when the direction of sound propagation was perpendicular to the major dendritic axis we could get about 30% change in velocity by rotating the shear cut transducer 90°. Independent studies at ORNL and at several other laboratories have shown[3,5,6] that the velocity of sound energy in both the shear and longitudinal modes can vary with the direction of propagation through materials having dendritic structures such as are found in most austenitic weldments.

Table 1. Acoustical data for transition joint materials

Material	Condition	Density (Mg/m^3)	Velocity, km/s		Normal acoustical impedance ($Gg/m^2 s$)
			Longitudinal	Shear	
Type 316 stainless steel	Wrought	8.00	5.74	3.10	45.9
2¼ Cr-1 Mo	Wrought	7.85	5.89	3.25	46.2
Alloy 800	Wrought	8.03	5.59	3.06	44.9
16-8-2	As welded	7.95	5.68	3.10	45.2
ERNiCr-3	As welded	8.30	5.33	3.26	44.2

Using the data in Table 1 and conventional techniques, we can show that all materials in the transition joint, including the weld metals, have approximately the same acoustical impedence. This means that very little acoustical mismatch occurs at the weld interfaces and very little sound energy will be reflected when a sound beam traverses the interface. The following equations[7,8] were derived for a liquid-solid interface for longitudinal waves incident perpendicular to the interface from the liquid.

$$\text{Acoustical impedence } Z = \rho V , \tag{1}$$

where

ρ = material density,

V = sound velocity.

$$\text{Acoustical mismatch } m = Z_2/Z_1 . \tag{2}$$

[6] L. Adler, K. V. Cook, W. A. Simpson, D. K. Lewis, and D. W. Fitting, *Ultrasonic Flaw Detection and Characterization in Structural Materials by Spectral Analysis,* ORNL/TM-G456 (October 1978).

[7] R. C. McMaster, ed., *Nondestructive Testing Handbook,* Vol. 11, The Ronald Press Company, New York, 1963.

[8] J. H. Smith, *Energy Redistribution in an Ultrasonic Beam Reflected at a Liquid-Solid Interface,* Y-1798 (July 9, 1971).

The subscripts 1 and 2 designate the materials.

$$\text{Reflection coefficient } R = \left(\frac{m-1}{m+1}\right)^2 . \tag{3}$$

$$\text{Transmission coefficient } T = 1 - R . \tag{4}$$

These equations also apply to normally incident shear waves at a solid-solid interface (where no mode conversion occurs). Assuming the materials are isotropic and homogeneous and using these equations and the data in Table 1, we can show theoretically for normal incidence that less than 0.1% of the sound energy reaching any of the four weld interfaces will be reflected. The amount of sound energy reflected by the weld interface is small because the two interface materials have very similar acoustical impedences. By comparison, a water-steel interface has an acoustical mismatch of about 30 and nearly 90% of the sound energy is reflected. If we also consider the anisotropy of the weldment, where shear velocity differences as large as 30% have been measured, the amount of sound energy will again vary (it can increase or decrease, depending on other parameters). Still, with all considerations being taken into account, it can be shown that very little of the sound energy incident at any of the four transition joint weld interfaces will be reflected.

The fact that most of the sound energy is transmitted into the weld has both good and bad features. For one thing, little energy is reflected by the interface itself, so defects such as interface cracks and lack of fusion, both of which have high acoustical mismatches, should be more readily detectable. On the other hand, when more energy is transmitted into the weld, more energy is available to be scattered and reflected by grain boundaries and precipitates, which also exhibit high acoustical mismatches. The resulting effect is that higher amplitude noise signals are reflected from the weld volume.

The acoustical attenuations of the materials involved were examined by the method of measuring the energy difference or loss between multiples for longitudinal waves. The energy loss between the second and third multiples and between the third and fourth multiples was determined and these two values were averaged. A correction for interface losses was made by use of the curve in Sect. 45.5 of the *Nondestructive Testing Handbook.*[7] The value was then divided by the sample thickness to get the attenuation per unit length. Using the above method and a 2.25 MHz test frequency we obtained attenuation values for type 316 stainless steel in the range of 100 to 150 dB/m. These measurements were made on the base plates of weld samples that had both surfaces ground smooth and flat. In general, attenuation was relatively uniform for a given plate; the variation or range of attenuation values were obtained over several samples. The same transducers and test setup were used for all measurements. The attenuations of the other transition joint materials were determined by the same procedure.

Sound attenuation is a very difficult property to measure, even when specimen and test conditions are controlled. We did not attempt to make absolute attenuation measurements; rather, we compared the attenuation properties of the materials used in the transition joint with that of type 316 stainless steel. Table 2 gives the range of multiplication factors that relate the attenuation of the indicated materials. All data were obtained at 2.25 MHz. The attenuation properties of these materials were also examined with 1 and 5 MHz test frequencies. The results were as expected, a slightly greater attenuation at 5 MHz and slightly smaller at 1 MHz, except for alloy 800; a significantly smaller attenuation for this material was noted at 1 MHz.

Table 2. Relative attenuation factors for transition joint materials at 2.25 MHz

Material	Attenuation factor
2¼ Cr-1 Mo	0.8–0.9
Type 316 stainless steel	1
Alloy 800	2–3
ERNiCr-3	3–5
16-8-2	3–5

This anomaly in alloy 800 reappeared when we examined the frequency spectrum of sound energy transmitted through the different base metals. Both longitudinal and shear wave modes were investigated. The test system was arranged in a two-transducer transmit-receive setup from one side of the 19-mm-thick flat test specimens. The sound path in the metal plate was a full V-path at a nominal 45° refracted angle, making the total path about 54 mm. Two matched wide-band 5-MHz transducers were used. (The pulses actually peaked at 5.25 MHz.) The results, which are shown in Figs. 4 and 5, are quite interesting. (Figures 4 and 5 do not show the relative amplitudes of the signals.)

The 2¼ Cr-1 Mo steel had little or no effect on the frequency envelope of either the longitudinal- or shear-wave signals. The frequency spectra of the received signals were identical to those for the transmitted signals. Therefore, the received signals from the 2¼ Cr-1 Mo steel are used as references in Figs. 4 and 5. Figure 4 shows the frequency spectra for longitudinal waves. A slight shift to a lower frequency can be noted for type 316 stainless steel, and a larger downward frequency shift occurs in alloy 800. Large and more obvious frequency shifts occur for the shear-wave signals, as can be seen in Fig. 5. The peak frequency for the shear-wave signal traveling through type 316 stainless steel is shifted downward to 3 MHz, and a significant shift to 1.25 MHz occurs in the alloy 800. Actually, alloy 800 acts very much like an ultrasonic filter, highly attenuating shear-wave sound energy for frequencies greater than 2 MHz.

These data helped to explain some of the earlier difficulties that were experienced with unusually high attenuation in alloy 800 when we used a 2.25 MHz shear wave test frequency. As a result of this information, we began using a 1 MHz frequency to examine the transition joint weld and weld interfaces, and the result was a significant improvement of inspection sensitivity for interfaces between alloy 800 and weld metal.

The grain sizes of the three base metals were examined, and the typical grain structures are shown in Fig. 3. The grain size of 2¼ Cr-1 Mo is small and relatively uniform. Type 316 stainless steel has larger grains, and they are not very uniform. The grain structure of alloy 800 is very nonuniform, and some unusually large grains can be found. The grain sizes of alloy 800 can vary considerably with different heats and within a given sample. The grain sizes of these base metals are compared with the wavelengths of sound energy traveling in steel for three frequencies in Table 3. The sizes of the maximum grains were measured on the metallographic samples from which the photographs in Fig. 3 were obtained. The wavelengths of the sound energy were calculated for the transition joint base metals from the velocities given in Table 1 with the following equation:

$$\lambda_i = v_i/f\,, \tag{5}$$

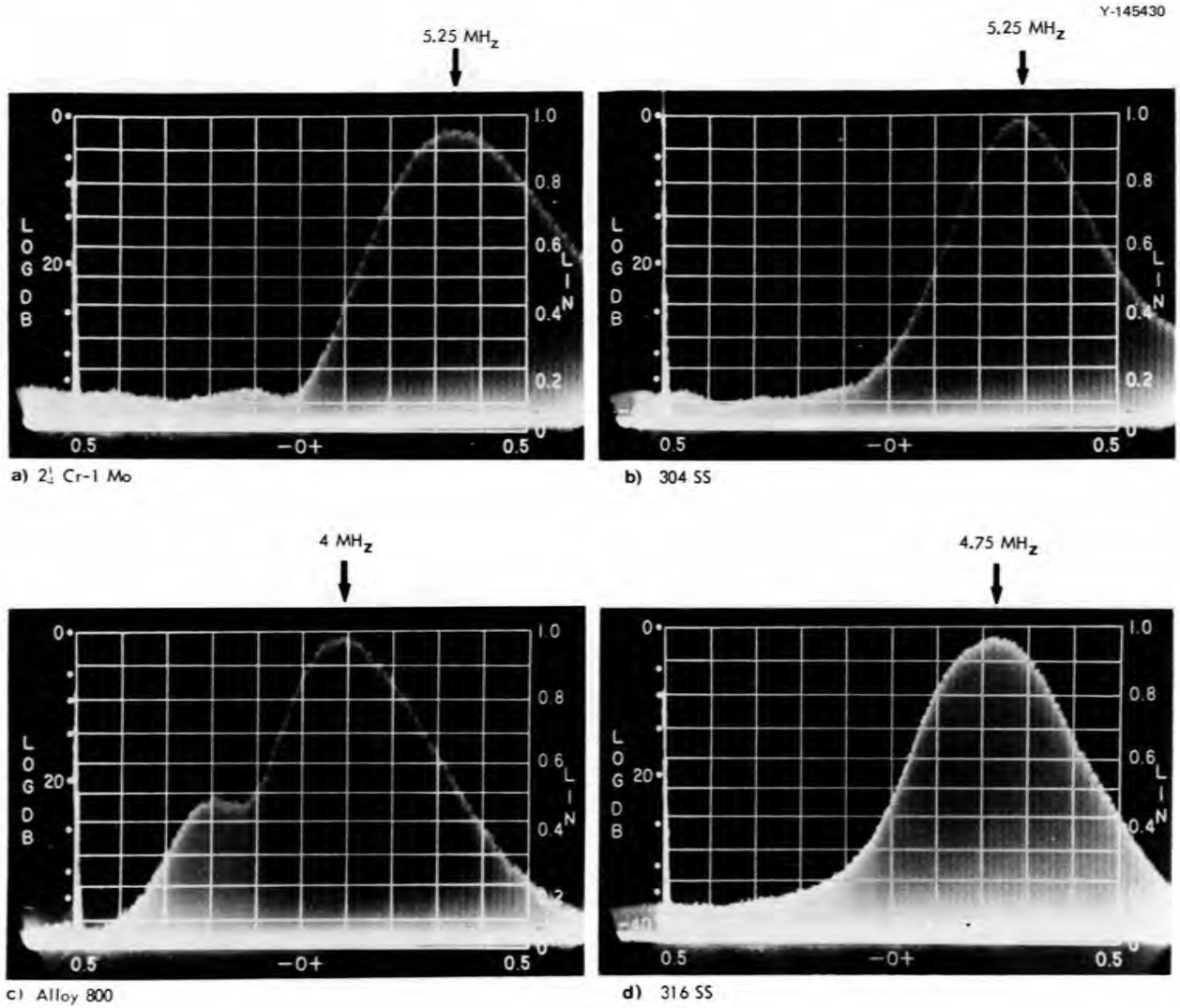


Fig. 4. Frequency spectra of 5.25-MHz wide-band longitudinal-wave pulse after propagating through 54 mm of (a) 2¼ Cr-1 Mo steel, (b) type 304 stainless steel, (c) alloy 800, and (d) type 316 stainless steel.

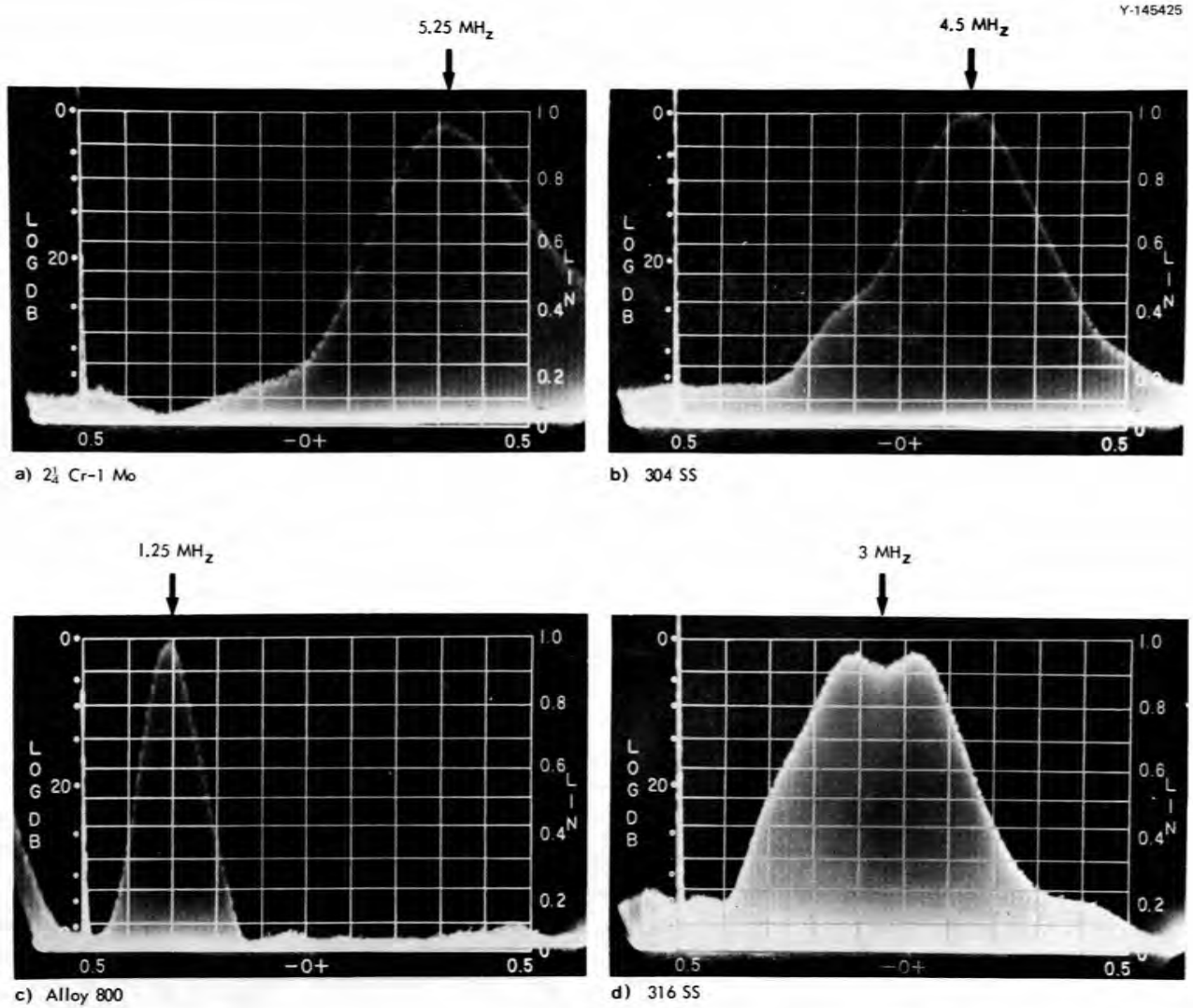


Fig. 5. Frequency spectra of 5.25-MHz, wide-band, shear-wave pulse after propagating through 54 mm of (a) 2¼ Cr-1 Mo steel, (b) type 304 stainless steel, (c) alloy 800, and (d) type 316 stainless steel.

Table 3. Grain sizes of and ultrasound wavelengths in transition joint alloys

Material	Grain size[a] (mm)	Wavelength, mm					
		1 MHz		2.25 MHz		5 MHz	
		λ_l	λ_s	λ_l	λ_s	λ_l	λ_s
2¼ Cr-1 Mo	<0.1	5.89	3.25	2.62	1.44	1.18	0.65
316 SS	≈0.4	5.74	3.10	2.55	1.38	1.15	0.62
Alloy 800	≈0.8	5.59	3.06	2.48	1.36	1.12	0.61

[a]Maximum length measured on metallographic sample.

where:

λ = wavelength

v = velocity of sound wave

f = frequency of sound wave

i = subscript l or s referring to longitudinal or shear waves

The data in Table 3 show that alloy 800 can have individual grains that are considerably larger than the nominal ASTM-5 grain size, which is specified for this material. These large grains are also bigger than the wavelength of shear waves at 5 MHz, and they approach the wavelengths of longitudinal waves at 5 MHz and shear waves at 2.25 MHz. These data help explain why the lower operating frequency of 1 MHz provided better test results for this material.

The random distribution of these large grains also offers an explanation for the variation in acoustical attenuation and for the isolated areas of unusually high attenuation that can be found in alloy 800. The same logic can be used to explain the unusually high attenuation and variation in attenuation that can be found in austenitic stainless steel weldments, where the dendritic cells grow epitaxially across the weld passes and can have lengths of several millimeters.

TEST PARAMETERS

Weld Test Samples

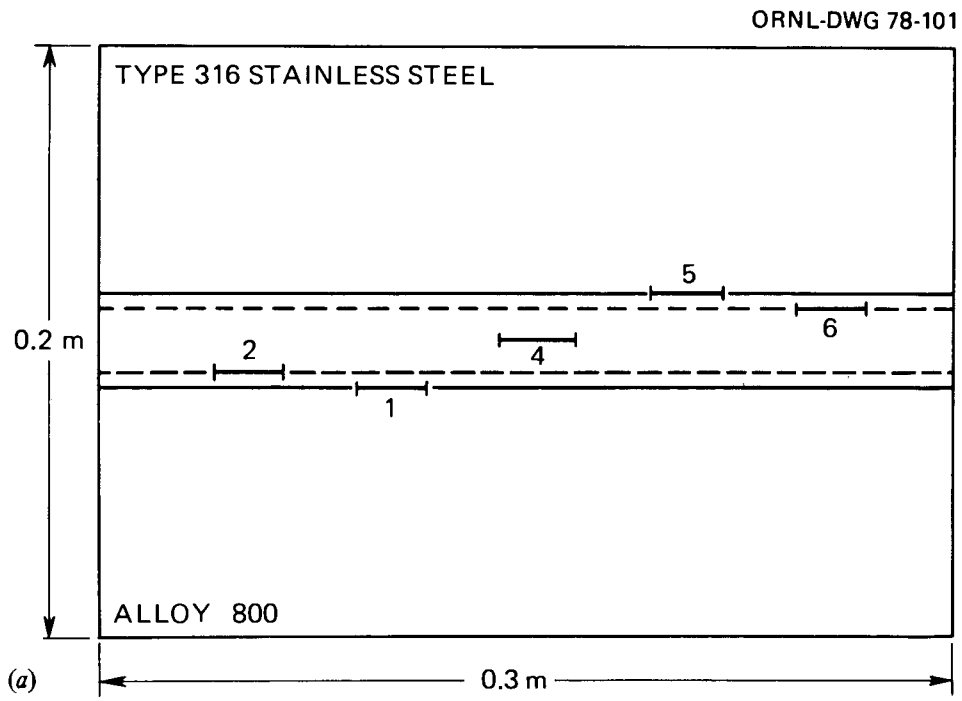
The weld test samples used in this study were fabricated with the materials, welding techniques, and joint design shown in Fig. 1. The weld samples were produced by the weld development laboratories at ORNL and at General Electric in San Jose, California. Figures of the weld samples used in this study along with the dimensions of the notches and manufactured discontinuities are included with the associated data discussion.

The faces of all weld samples were ground flat to represent in-service conditions. Fortunately, this grinding eliminated from the weld crown and weld root areas many surface reflectors that would normally be sources of noise. The final thicknesses of the weld samples were nominally either 12.7 or 25.4 mm. All welds were radiographically inspected before and after grinding, and the results indicated no defects and very little porosity in any of the welds.

We examined various different types of manufactured discontinuities, such as flat-bottom holes (FBH), side-drilled holes (SDH), hemi-spherical cavities, circular-saw-cut notches, and electrical-discharge machined (EDM) notches in the weld samples. These reference reflectors were placed in the base metal, at the weld interface, and in the weld proper on both the root and crown surfaces of the weld samples. These

discontinuities were distributed along the weld so the reflected ultrasonic signals would not interfere with each other, see Fig. 6(*a*). Comparing the above-mentioned discontinuities, notches and SDHs provided the best reference reflectors for these tests; therefore, most of our sensitivity data and detection capabilities will be related to these reflectors.

The depths of all notches were measured with an optical microscope with a micrometer stage and a calibrated dial indicator. The referenced depth of the circular-saw-cut notches in this report is always the maximum measured depth. The diameters of all holes were measured by using the shanks of drill bits as go no-go gages and then measuring the diameters of the drill bits with a calibrated micrometer. All measurements were checked independently.



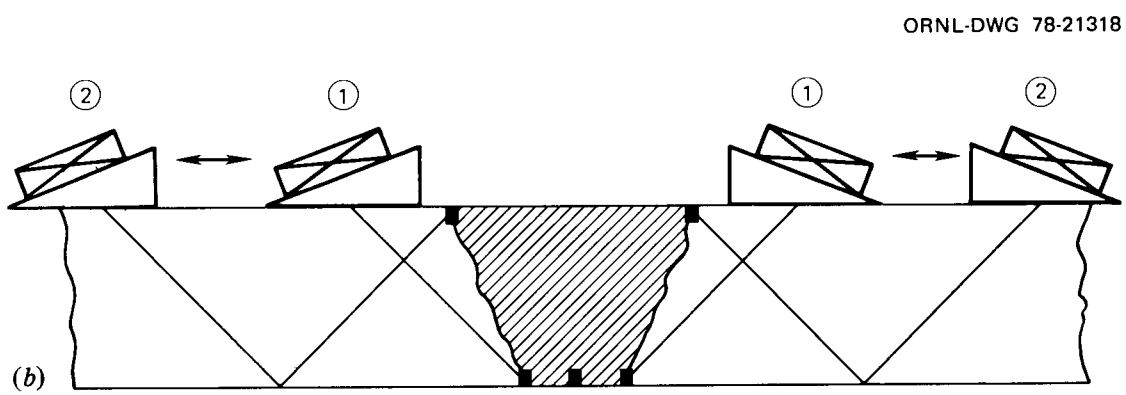


Fig. 6. Transducer positions and location of notches in weld samples. (a) Surface view. (b) Side view.

All prototypic weld samples used in this study were flat, but little difficulty was experienced in transposing test data obtained on flat specimens with a 13-mm-diam transducer to pipe welds having 457 and 660 mm diameters. (These are the diameters of the 12.7- and 25.4-mm-thick pipes.) Independent tests were made to determine the ability of these procedures to inspect a 203-mm-diam 8.2-mm-thick type 316 stainless steel pipe weld, and no difficulties were experienced. At the time of this writing tests have just been completed on CRBR transition joint life tests using prototypic welds, and again no difficulty was experienced.

Referring to the flat weld samples, the weld crown face of the sample represents the outer surface of a pipe weld and the root surface area represents the inner surface of a pipe weld.

Testing Techniques

Most of the data in this report were obtained with an ultrasonic immersion test system. Immersion techniques were used because they provided more control over the test, mechanical scanning techniques could be used to assure that 100% of the weld was inspected, and we had more flexibility to vary test parameters such as the incident and refracted angles to optimize test sensitivity. The data are also more repeatable because much of the human error present in manual scanning is eliminated. A sufficiently long water path was maintained during the immersion tests to assure that the weld areas being inspected fell in the far field zone of the sound beam for the particular transducer and frequency being used.

Some manual contact scans were performed on these weld samples and found that, in general, the instrument gain setting had to be increased slightly to detect a given manufactured discontinuity at the same amplitude as for an immersion test. The typical weld noise level is quite difficult to determine by manual contact techniques, but theoretically the signal-to-noise ratio should not differ significantly from that determined by immersion techniques. Using contact methods, we could easily detect any manufactured discontinuity mentioned in this report for which a 2:1 signal-to-noise ratio could be obtained by immersion techniques. Smaller reflectors are more difficult to detect routinely, and considerable emphasis is placed on the skill and alertness of the operator. Contact scanning definitely requires practice and experience for proficiency.

All data in this report were obtained by ultrasonically inspecting the welds from the crown surface, since these test techniques will eventually be used on pipe welds, where only the outer (crown) surface is accessible. It was necessary to inspect each weld from both sides on the crown surface because each side of a dissimilar-metal transition joint weld presents a different acoustical impedence and therefore a different problem for ultrasonic inspection.

Refracted shear- and refracted longitudinal-wave techniques, using both single- and dual-transducer arrangements, were applied during this study. Longitudinal-wave techniques tend to provide better penetration in the highly attenuative materials such as austenitic welds and alloy 800. Data obtained during this study showed that increasing the wavelength will give shear waves better penetrating ability in austenitic welds, but longitudinal waves still appear to penetrate weld metal slightly better than shear waves, even when both have the same wavelength. This increase in penetrating ability may be related to the direction of particle vibration within the cellular dendritic structure. The dual-transducer longitudinal refracted wave technique is more complicated than a routine single-transducer shear wave method. For one thing, refracted longitudinal waves can not be generated without also generating shear waves, and these additional signals increase the noise level and make data interpretation more difficult. This method also requires a more intricate calibration procedure and more precise ultrasonic instrumentation to gate out unwanted signals. Selective gating techniques may be used to eliminate many of the unwanted signals present during both refracted longitudinal- and refracted shear-wave tests.

The dual-transducer transmit-receive arrangement helps reduce the recorded noise level by omitting those signals that could normally be reflected by the transmitted beam, but this arrangement has the disadvantage that the effective sound path is equivalent to that of a focused beam,[9] only a limited area can be inspected, and different test setups must be used to inspect different depths. We also found that test sensitivity diminishes rapidly when one exceeds a half V-path and tries to bounce focus the two beams.

The improved noise level makes the dual transducer arrangement a bonus for longitudinal wave testing, but a single transducer arrangement worked best for the shear wave tests used in this study. We found that the focusing effect of a dual transducer system made the inspection of an entire weld interface difficult to perform with a single test setup, and the improvement in noise level was not a significant factor for our shear test arrangement.

Several different testing techniques were investigated, but we resolved to using only dual transducer longitudinal waves and single transducer shear waves. Then experimental data showed that a single transducer shear wave technique could fulfill the requirements of this test if we used multiple test frequencies. Upon gaining this information we limited our study to shear wave techniques, and most of the data in this report were obtained by use of single transducer 45° refracted shear wave method.

We tried several different refracted angles in the range from 30 to 70°, and we obtained our best results with angles around 45°. While conducting this examination we noted that sometimes just a small change in the refracted angle (1–2°) can cause a significant change in the amplitude of the reflected signal. This points out a need for more versatile mechanized weld scanning equipment having the necessary degrees of freedom to properly optimize the reflected signal from a given discontinuity. This variability, if properly scaled, could provide additional information about the orientation of the reflecting surfaces.

We investigated several different sizes and types of ultrasonic transducers, including tuned, untuned, and focused. Test frequencies varied from 0.5 to 10 MHz for this inspection, and we considered such factors as beam spread, area of inspection, and speed and ease of the inspection. Although these studies may not be conclusive, we obtained our best results using 12.7-mm-diam, tuned, flat transducers. (All data discussed in this report were obtained with this type of transducer). Basically, we found that higher frequencies (smaller wavelengths) do not penetrate weld metals as well as lower frequencies, but resolution decreases when lower frequencies are used. The optimum test frequency is a compromise between good resolution and sufficient penetration to obtain the optimum test sensitivity with a signal-to-noise ratio that is large enough to routinely distinguish defect signals from the typical weld noise level. Most of the data in this report were obtained with 1, 2.25, and 5 MHz test frequencies. We did not use test frequencies that are not typically available on standard commercial ultrasonic test equipment.

In summary, we found that no single technique or test frequency results in optimum sensitivity for all test conditions. The optimum testing technique and frequency may vary depending on the area of the weld (root, crown, interface) being inspected, the type of materials involved, geometrical and environmental conditions, the type of defect desired to detect, and the type most likely to occur,[10] among other things.

Test Equipment

Figure 7 shows the test equipment and setup used in this study. The immersion tank uses water as a couplant and contains a typical *x-y* scanning mechanism. The ultrasonic instrument is an Automation

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[9] G. Herberg, W. Müller, O. Ganglbauer, "Preliminary Results for Practical Ultrasonic Testing of Austenitic Steel Welds," *Non-Destr. Test.* (Guildford, Engl.) *9*(5):239–41 (October 1976).

[10] G. J. Dau, "Summary of Problems and Recommended Solutions for Inservice Inspection of Austenitic Piping," presented at Nondestructive Examination Conference, Washington, D.C., Nov. 18, 1976.

Fig. 7. Ultrasonic test equipment.

Industries Model S-80 reflectoscope, and the transducers used were manufactured by Harrisonics, Aerotech, and Panasonic. To produce C-scan recordings, a standard x-y recorder (Hewlett-Packard, model 1204) is connected to the ultrasonic instrument and mechanical scanning mechanism through a recorder adaptor. Figure 8 shows the test setup for the dual-transducer longitudinal refracted wave technique. The same system, employing only one transducer, was used for the shear wave tests.

Scanning Techniques

The C-scan recordings shown in this report were produced by scanning the ultrasonic transducer back and forth along the axis of the weld with the sound beam incident on the base metal at the crown surface of the weld sample. At the end of each scan the 13-mm-diam transducer was indexed either toward or away from the weld by a distance of 1 mm. (The distance between any two consecutive lines on a C-scan recording therefore represents approximately 1 mm at the weld interface.)

The width and length of the C-scan recording approximate the weld sample dimensions, but the relationship is not exact. The tests were usually begun with the transducer at least a distance of $2T \tan \gamma$ away from the weld, where T = weld thickness and γ = refracted angle; see position 2, Fig. 6(b). This assures that the sound beam will impinge on the crown (outer) corner of the weld interface after having traveled a full V-path in the base metal. The transducer is then indexed toward the weld (while scanning) until the sound beam contacts the root (inner) corner of the weld interface, position 1, Fig. 6(b). The sound beam at

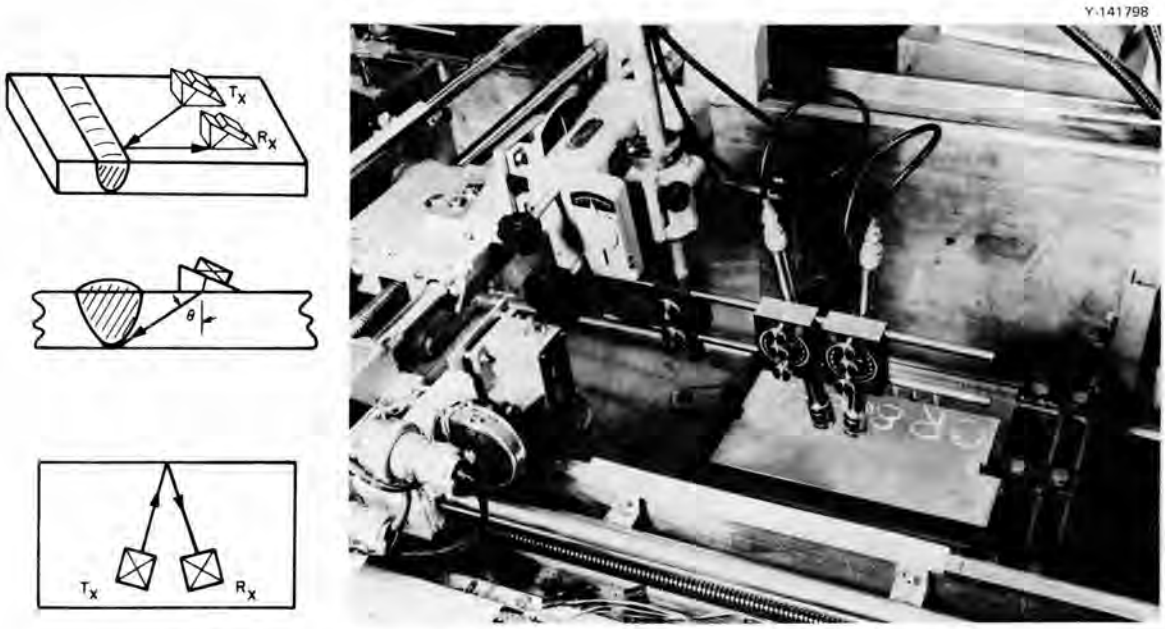

Fig. 8. Equipment used for the dual transducer longitudinal refracted wave technique.

this point travels a half V-path. The C-scan that is produced represents an inspection of the weld interface nearest the transducer. The far weld interface is inspected by moving the transducer to the other side of the weld and repeating this process, staying on the crown surface of the weld sample. We found that we could obtain fairly good test sensitivity for weld interface inspections. The typical noise level is relatively low, and sound energy does not have to travel through a significant amount of weld metal to inspect a weld interface. As was shown earlier, most of the sound energy incident at a weld interface is transmitted through the interface unless a discontinuity exists. Saw-cut and EDM notches placed at the weld interface on the root and crown surfaces of the weld sample [darkened rectangular areas in Fig. 6(b)] were used to determine test sensitivity. We also placed notches in the center of the weld root to determine test sensitivity for that area. In order to inspect the weld root volume we had to index the transducer in toward the weld from Position 1 in Fig. 6(b). This is sometimes impossible when the as-welded weld crown exists, but fortunately these transition joint welds have the weld crowns ground smooth.

Gating and Distance-Amplitude Corrections

Gating is an electronic technique used in ultrasonic testing where the operator can select to be recorded only those signals that have a predetermined amplitude and fall within a given time period on the oscilloscope. Figure 9(a) shows two gates (short distinct horizontal lines) set at different amplitude levels on the ultrasonic instrument's cathode ray tube (CRT). The signals shown below the gates will not be recorded unless they occur in the same time frame and exceed the amplitude of the gates. Typically, only one gate is used and, in fact, most of the data in this report were recorded by use of a single gate. The C-scans shown in this report were all made with the gate amplitude level set at 50% unless otherwise indicated. This means that the received signal was recorded only if it exceeded a 50% amplitude on the CRT scale. The period of the gate was set to record any signal occurring in time from the root to crown area of the weld, unless otherwise noted. For some tests (in weld samples about 25 mm thick), we had to gate the root and crown areas individually to optimize signal-to-noise ratios.

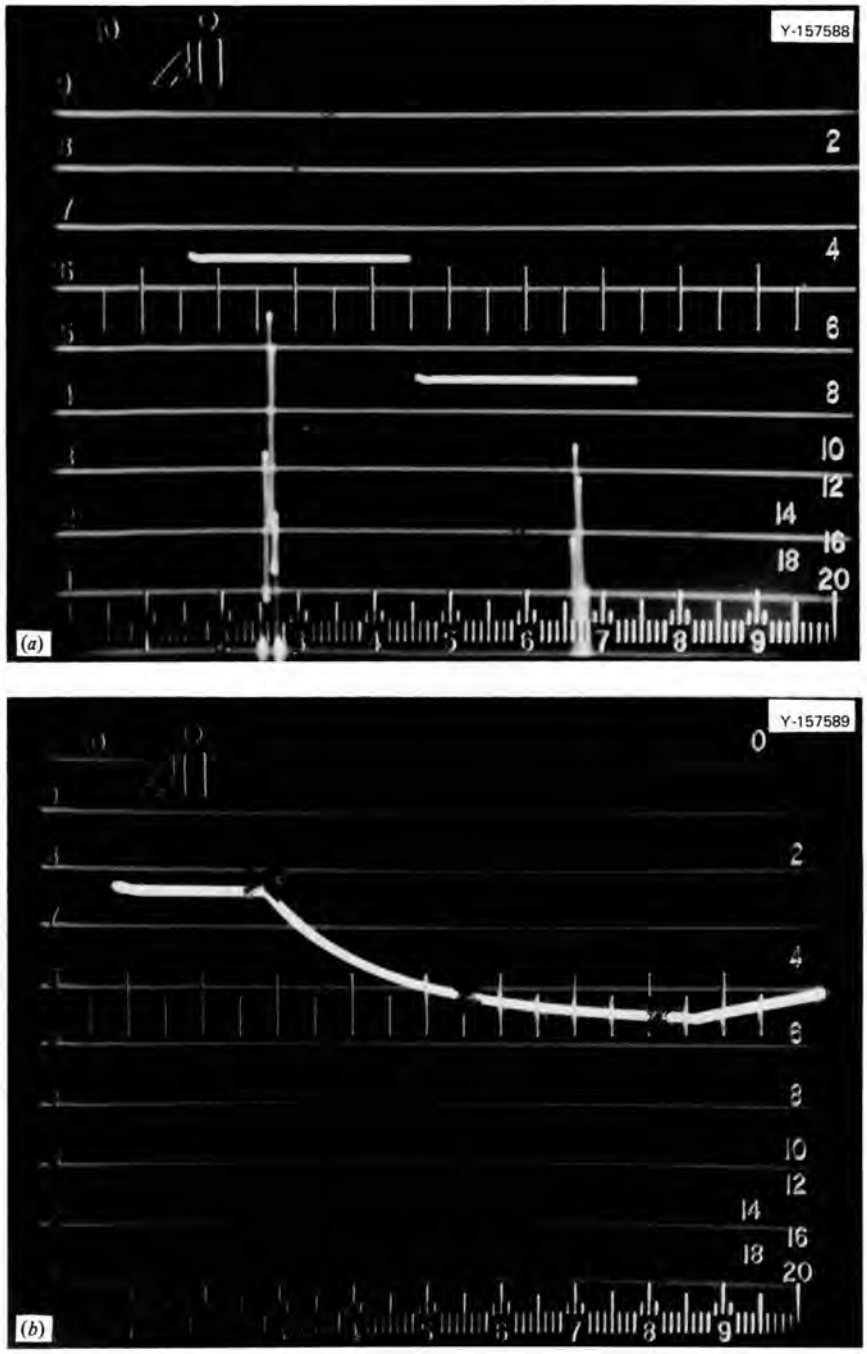

Fig. 9. Examples of gating and distance-amplitude corrections. (a) Dual gates. (b) Electronic D-A correction.

Distance-amplitude corrections are made to account for losses in signal amplitude due to attenuation by the test material. They usually apply when highly attenuative materials are inspected and/or when the sound wave must traverse significant thicknesses of a material. For example, in pipe welds where only the crown surface is accessible, the sound beam travels a ½ V-path to detect a weld root notch, whereas it must travel a full V-path to detect a weld crown notch. If the two notches are the same size and shape the two reflected signals will probably not have the same amplitude because of the different distances traveled by

the sound beam. Distance-amplitude corrections are made to account for this difference in the signal amplitudes. Historically, these corrections have been made manually, but some modern ultrasonic instruments are equipped with electronic circuits that provide distance-amplitude correction. Figure 9(b) shows an example of an electronic D-A curve. Accepted techniques for producing D-A curves can be found in the *ASME Boiler and Pressure Vessel Code.*[11] Specific applications of gating techniques and distance-amplitude corrections will be discussed later in this report.

WELD NOISE LEVEL AND SIGNAL-TO-NOISE RATIO

A determination of test sensitivity for an ultrasonic weld inspection requires more information than just the minimum size reflector that can be detected in a localized weld area. It requires a knowledge of the amplitude and distribution of noise levels over the entire weld for the specific ultrasonic test conditions being applied. True test sensitivity should be related to the minimum size reflector that can be routinely detected above the typical weld noise level. For example, a 0.1-mm-deep EDM notch can be easily detected ultrasonically through 13 mm of base metal for either 2¼ Cr-1 Mo steel or type 316 stainless steel, but at the same test sensitivity noise signals that can exceed the amplitude of the signal from the same EDM notch can be obtained from either weld interface or from the alloy 800 base metal.

Weld noise is generally thought of as those recorded signals originating in the weld area for which the source can not be explained. There are also many sources of noise, generated during weld inspections, that can be defined. These include weld root corners, weld undercut, backing strips, and machined edges. The typical weld noise level is difficult to determine when one uses manual contact methods and visually observes the CRT presentation. This is one area where a permanent recording can definitely improve inspection capability.

Many of the C-scan recordings shown in this report are presented at several different gain levels (expressed in decibels). The lowest gain levels were chosen to show the minimum gain where a given reference reflector can just be detected at an amplitude greater than 50% on the CRT scale. The gain level was then increased incrementally to the point where noise is first recorded from the weld. Subtracting the gain where the signal is first recorded (at 50% amplitude) from the gain where noise is recorded provides a nominal signal to noise level expressed in decibels. The decibel value can be converted to a ratio by use of tables or the following equation.

$$\mathrm{dB} = 20 \log_{10}(A_1/A_2) \tag{5}$$

where A_1/A_2 is the ratio of two amplitudes.

For example, a 6-dB difference represents a 2:1 signal to noise ratio.

The typical weld noise level and the signal-to-noise level for a given manufactured discontinuity can be obtained from many of the C-scan recordings shown in this report by the above-mentioned techniques. The other method of data presentation used in this report shows C-scan recordings of the various reference reflectors with no noise signals present on the recording, indicating a test capability.

[11] "Article 5, Ultrasonic Examination," pp. 37–46 in *ASME Boiler and Pressure Vessel Code, Sect. V, Nondestructive Examination,* American Society of Mechanical Engineers, New York, 1977.

DISCUSSION OF TEST RESULTS

Since each side of the two transition joint welds presented a different acoustical problem for ultrasonic inspection, the four different weld interfaces will be discussed individually. In each case the sound beam was incident from the base metal side of the interface on the crown surface of the weld sample.

Weld Interface of 2¼ Cr-1 Mo and ERNiCr-3

Figure 10 shows one of the early weld samples that we ultrasonically examined. This sample, identified as CR800-13, represents the 2¼ Cr-1 Mo/ERNiCr-3/Alloy 800 weld joint. It was fabricated by welding a 19-mm-thick plate of 2¼ Cr-1 Mo steel to an alloy 800 plate of similar thickness as described previously. After welding, the root and crown surfaces of the weld sample were ground flat and smooth to represent in-service conditions. This grinding provided a final sample thickness of 16 mm. We experimented with a variety of ultrasonic reference reflectors, such as side-drilled holes, saw-cut notches, through holes, and hemispherical cavities to compare their response and to determine which provided the better reference reflector for calibration. These manufactured discontinuities and their associated dimensions are described in Table 4. All notches were cut with a circular saw blade, giving the notches the shape of a segment of a circle.

Figure 11 shows the results obtained when weld test sample CR800-13 was ultrasonically inspected from the 2¼ Cr-1 Mo side by a single-transducer 45° shear-wave technique at a test frequency of 1 MHz. The tests used an immersion setup, and the sound beam, which was always incident on the crown surface of the weld sample, was indexed completely across the weld.

Indications 1, 3, 4, and 5 represent the respective manufactured discontinuities located in the base plate, see Table 4. Discontinuity 2 (hemispherical cavity) on the root side of the 2¼ Cr-1 Mo base plate does not produce an indication on this scan. It could be detected but required a higher instrument gain. As scanning continued and the transducer was indexed closer to the weld, notch 6 was detected with the sound beam traveling a full V-path in base metal. Notch 6 is located on the crown surface at the near weld interface. When the transducer was moved even closer to the weld, notches 7 and 8 were detected with the sound beam traveling a half V-path in base metal. We did not detect the midplane discontinuity (14, Fig. 10) on this scan; this will be discussed in more detail later. As the transducer is indexed even closer to the weld we detected notch 11, which is located at the far weld root interface, along with the two edges or corners of the weld sample. The sound beam must travel a half V-path through the weld metal to detect notch 11. Notch 9 could be detected but required a higher gain setting. Notch 7 interfered with the detection of notch 10 from the 2¼ Cr-1 Mo side of the weld. Scanning on across the weld sample we detected notches 13 and 15 located in the alloy 800 base metal. Hemispherical cavity 12 (Fig. 10) could be detected but required a higher gain setting. It should be noted that, with the exception of the two corners and the indication from an incomplete weld area at the left edge, no noise signals are present on the C-scan.

We have since obtained better test sensitivity on other weld test samples, but this sample and the associated data are included in this report to show the variety of manufactured discontinuities that were examined. This specimen (CR800-13) also highlights an error that frequently is made in the preparation of test samples: trying to place too many discontinuities in a single sample. This problem occurs more often when only a limited number of samples are made available for study; therefore, careful planning should precede placing any discontinuities in a reference standard to be sure that their location does not influence or bias the test results.

There is reason to believe that midplane weld interface flaws are more difficult to detect ultrasonically than surface-associated flaws. The major impediment to the investigation of this problem lies in the difficulty of simulating midplane interface flaws. One approach that we tried was to drill a flat bottom hole

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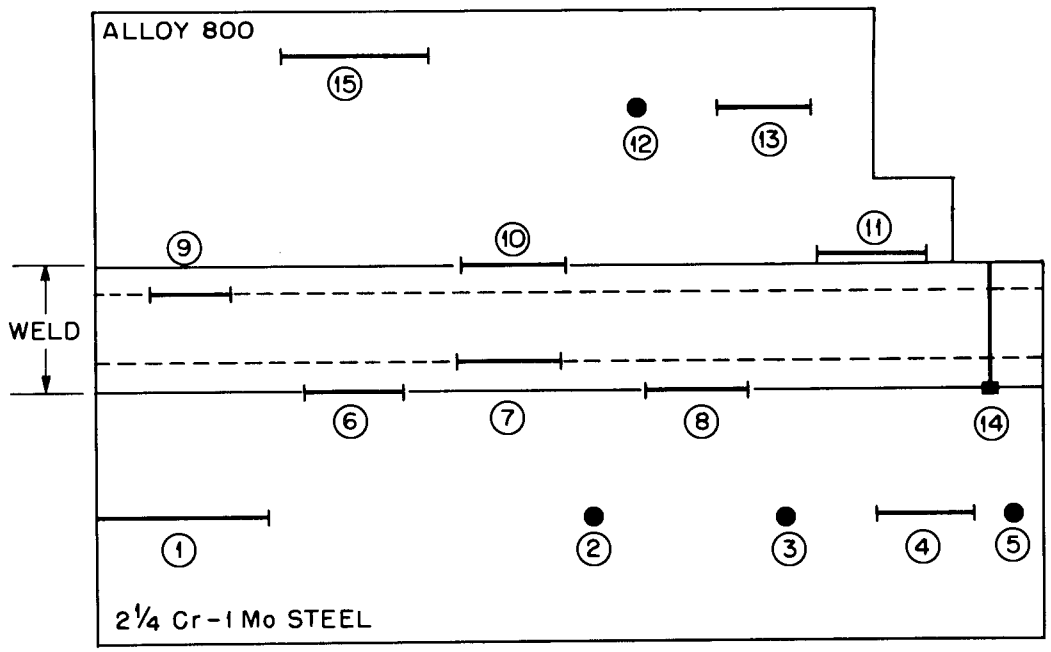

Fig. 10. Weld test sample CR800-13. Weld thickness 16 mm.

Table 4. Description of fabricated discontinuities shown in Fig. 10

Identity	Type	Surface	Dimensions, mm		
			Diameter	Depth	Length
1	Side-drilled hole		3.2	*T*/2	50.8
2	Hemispherical cavity	Root	3.2	1.6	
3	Through hole		3.2		
4	Notch	Root		1.6	25.4
5	Flat-bottom hole	Root	3.2	7.6	
6	Notch	Crown		2.1	28.6
7	Notch	Root		1.4	23.9
8	Notch	Root		1.8	26.9
9	Notch	Root		1.4	24.0
10	Notch	Crown		1.5	24.6
11	Notch	Root		2.1	28.4
12	Hemispherical cavity	Root	3.2	1.6	
13	Notch	Root		1.2	21.3
14	Interface FBH	Root	3.2	*T*/2	
15	Notch	Crown		3.8	38.8

(FBH) at an angle through the weld such that the flat end surface of the hole fell in the plane of the weld interface. This interface FBH is identified as discontinuity 14 in Fig. 10. This technique does not provide a satisfactory solution to the problem because these interface FBHs are very difficult to fabricate and the test results are really not very definitive. The base metal on one side of the weld must be cut away almost to the weld interface to provide an entry area to drill the hole at the correct angle. The exact length of the hole is difficult to determine because of the irregularity of weld interfaces. The diameter of the hole is restricted by the length of available drill bits capable of reaching the opposite interface and capable of drilling

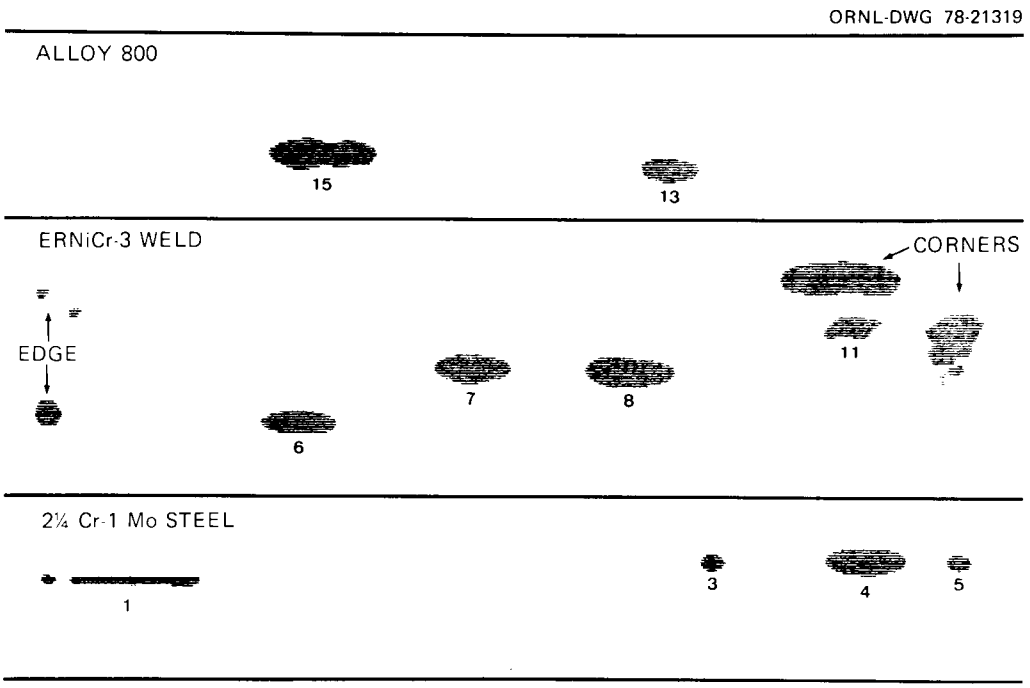

Fig. 11. C-scan results of 1-MHz single-transducer shear-wave inspection of weld sample CR800-13 when scanned from 2¼ Cr-1 Mo steel toward the weld.

through stainless steel. The size of the drill chuck and the required length of drill bit gripped in the chuck are restricting factors. When the weld interface is ultrasonically inspected, the cutaway section at the back of the weld creates corners that reflect quite large signals that can mask the signals reflected from the FBH. Another major factor is that a weld interface is not planar but very irregular and undulating, so it will be very difficult to fabricate any kind of discontinuity that will exactly follow the contour of the interface as a crack or natural defect might do. We could ultrasonically detect interface FBH 14 because we knew it was there; however, we could not detect it distinctly above the weld noise level.

Another approach examined during our attempt to investigate the ultrasonic response from midplane flaws was to place internal manufactured discontinuities at the weld interface during the welding operation. These discontinuities, which are not visible on the surface of the weld sample, were produced by tack welding over strips of mica at the beveled surface of one base plate before the welding operation. The V-joint weld was then completed in the normal manner. This sample, which is shown in Fig. 12, is made up of two 13-mm-thick type 316 stainless steel plates welded together with 16-8-2 filler metal by a GTA weld procedure. All parameters were such that the weld interface represents one of the 13-mm-thick transition joint weld interfaces. The dimensions of the mica strips were 25.4 by 1.3 by 0.25 mm. Four of these strips were placed at various depths at the weld interface with their major dimension parallel to the weld axis. Half of a mica strip (12.7-mm length) was placed perpendicular to the weld axis at the interface.

This sample has not been ground, and all nondestructive inspections were performed with the sample as welded. All five discontinuities were accurately detected and located by both ultrasonic and radiographic techniques. The scales are different, but Fig. 13 shows excellent agreement between the results of the two inspection methods. Both techniques confirmed that one mica strip had broken up during welding, probably from overheating. (This strip is shown as three sections in Fig. 12.) On both ultrasonic and radiographic inspections the other four mica strips produced discontinuity indications that agree quite well

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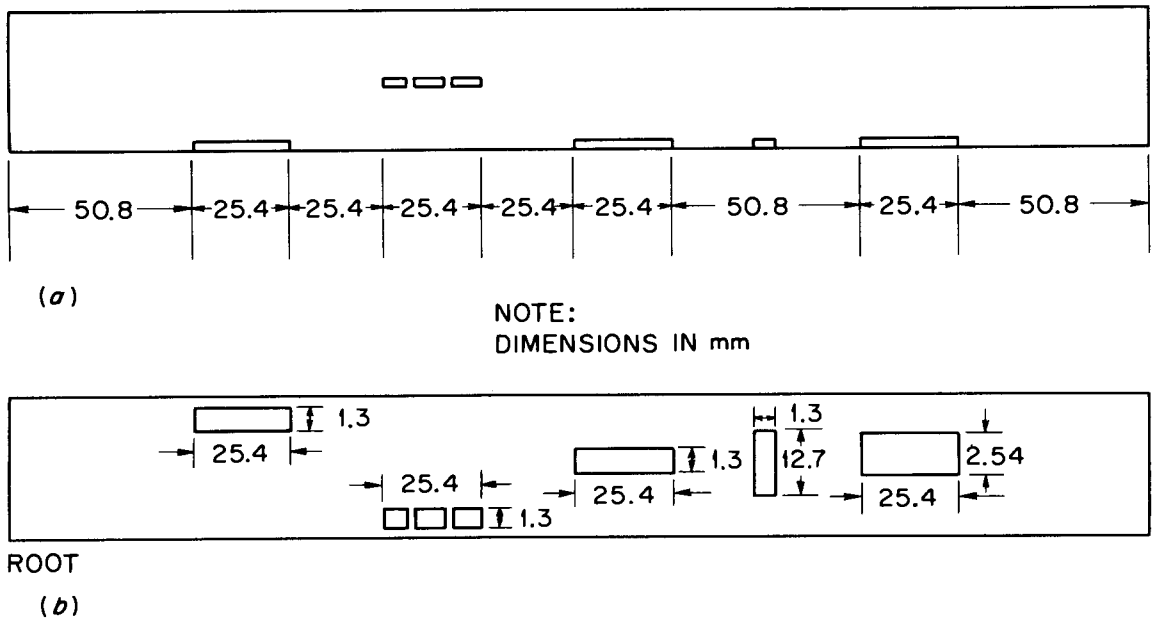

Fig. 12. Two views of 13-mm-thick weld test sample V204, showing locations of the simulated discontinuities. (a) Top view of stainless steel weld. (b) Side view of weld interface.

with the size and orientation of the mica strips. Figure 13(a) shows a photograph made from the radiograph of the weld. The arrows point out the locations of the mica strips at the weld interface (white areas). Figure 13(b) shows the C-scan results of a 2.25-MHz shear wave inspection of the same weld interface at three different instrument gains. These data show a capability to detect midplane interface discontinuities, but we are not sure how well the data relate to actual interface defects such as cracks and lack of fusion. This type of weld sample is fairly difficult to fabricate because the heat produced by the weld tends to melt and

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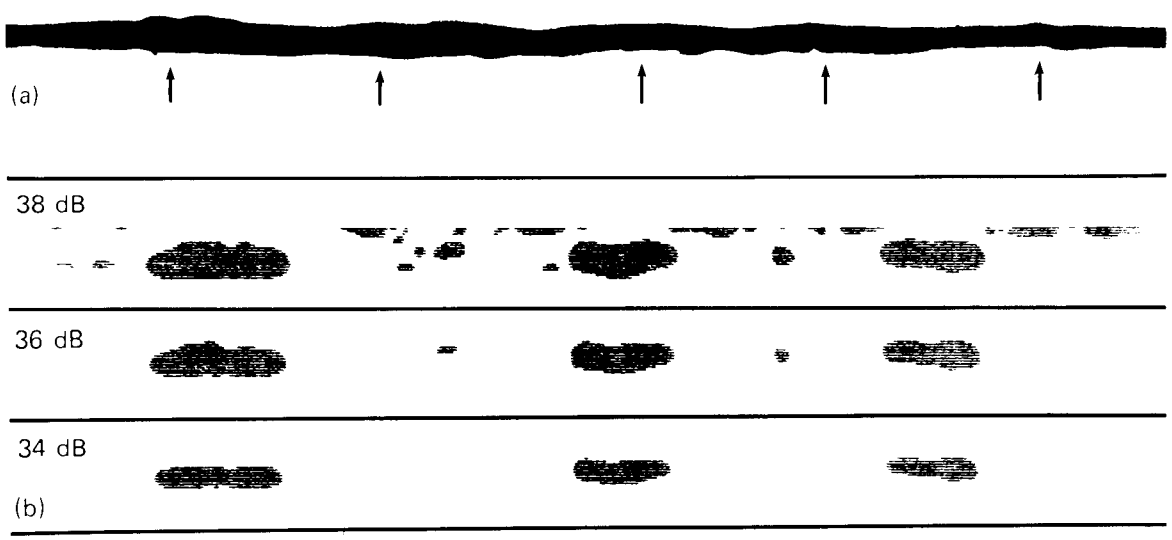

Fig. 13. Results of (a) radiographic and (b) 2.25-MHz ultrasonic inspections (single-transducer shear wave) of weld test sample V204.

evaporate the mica. Another simple method of determining test sensitivity to midplane flaws being investigated is to examine the ultrasonic response reflected from side-drilled holes located at the weld interface. The data will be published later in another report.

Weld test sample CR800-12A (Fig. 14, Table 5) was fabricated in the same manner as CR800-13. It has saw-cut notches on both the root and crown surfaces of the base metal, at the weld interfaces, and in the root of the weld proper. Even-numbered notches are on the root surface and odd-numbered notches are on the crown surface of the weld sample. Figure 15 shows the results of ultrasonically scanning weld sample CR800-12A from the 2¼ Cr-1 Mo side of the weld at several different gain settings, using shear-wave techniques and a test frequency of 1 MHz. Only those notches located at the weld interfaces or in the weld proper are recorded. The amplitude of the respective indications in percent of scope height at the various gain settings is also shown on the recording. The instrument gain settings are expressed in decibels (dB) at

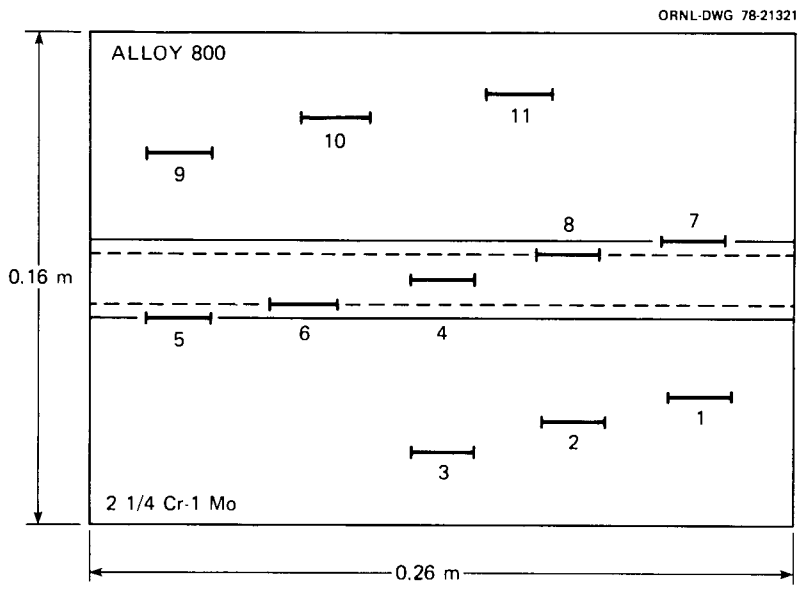

Fig. 14. Weld test sample CR800-12A. Weld thickness 15 mm.

Table 5. Descripton of notches shown in Fig. 14

Notch	Location	Surface	Notch Dimensions, mm		
			Depth	Length	Depth (%*T*)
1	Base	Crown	0.8	17.8	5.3
2	Base	Root	0.6	16.0	4.0
3	Base	Crown	0.7	17.1	4.7
4	Weld	Root	1.5	24.9	10.0
5	Interface	Crown	1.6	25.4	10.7
6	Interface	Root	1.5	25.1	10.0
7	Interface	Crown	1.6	25.4	10.7
8	Interface	Root	1.6	25.4	10.7
9	Base	Crown	1.7	25.9	11.3
10	Base	Root	1.5	25.0	10.0
11	Base	Crown	1.7	25.9	11.3

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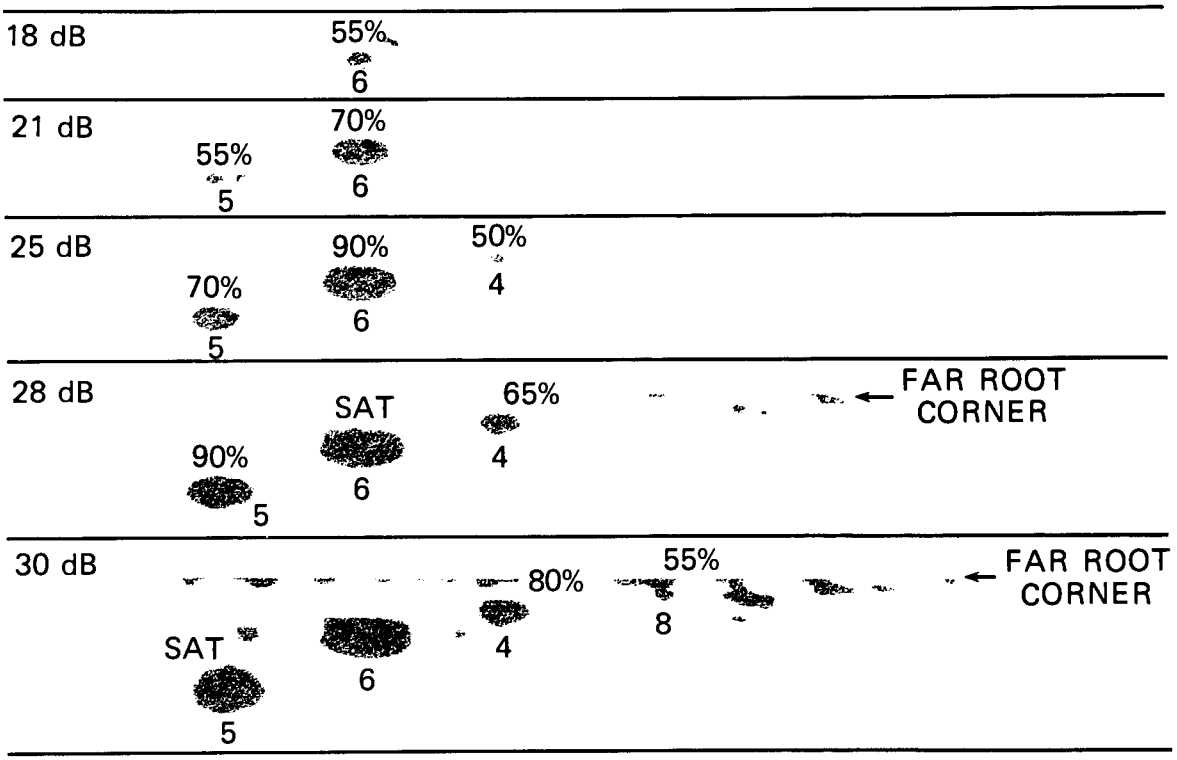

Fig. 15. C-scan results of 1-MHz shear-wave inspection of weld sample CR800-12A scanning from 2¼ Cr-1 Mo toward the weld.

the left side of the figure. The depths of notches 4 through 8 are approximately 10% of the thickness of the weld. The root and crown interface notches (5 and 6) and notch 4 in the center of the weld root can be detected quite distinctly above noise level. Notch 8, at the far root interface, is partially masked by the large signal reflected from the far root corner, which occurs all along the weld. This signal is reflected because a metallurgical difference in material combines with a geometrical corner. This signal is not uncommon and it does not always occur; however it is always a potential problem during a weld inspection. Using a different test angle or test frequency can reduce the amount of energy reflected from this metallurgical corner but may also reduce test sensitivity and gain nothing. The fact that we detected notch 8 (located at the far root interface) shows that we have test sensitivity across the weld root volume, but the weld should be inspected from both sides (on the crown surface) to obtain optimum test results.

The previous data have shown an inspection capability for the 2¼ Cr-1 Mo/ERNi Cr-3 weld interface in 13-mm-thick welds. Next we determined the optimum test sensitivity and optimum signal-to-noise ratio obtainable. One of the parameters varied was the test frequency. We examined the weld test samples using 1-, 2.25-, and 5-MHz transducers. (We investigated only frequencies that were available on standard ultrasonic test equipment.) Our results show that the 1 MHz frequency penetrates weld metal and coarse-grain materials such as alloy 800 better than either 2.25 or 5 MHz, but we begin to lose resolution, and small notches (<0.5 mm deep) become difficult to detect. On the other hand 5 MHz provides much better resolution but it apparently will not penetrate austenitic weld metal. The optimum test frequency therefore depends on what area of the weld is being inspected. When the 2¼ Cr-1 Mo/ERNiCr-3 weld interface is inspected from the base metal side by shear-wave techniques, better signal-to-noise ratios are obtainable for small reflectors when we use a 5 MHz test frequency. Figure 16 shows 15-mm-thick weld sample CR800-12. All notches were cut with a circular saw blade, and their dimensions are shown in Table 6. Note that the

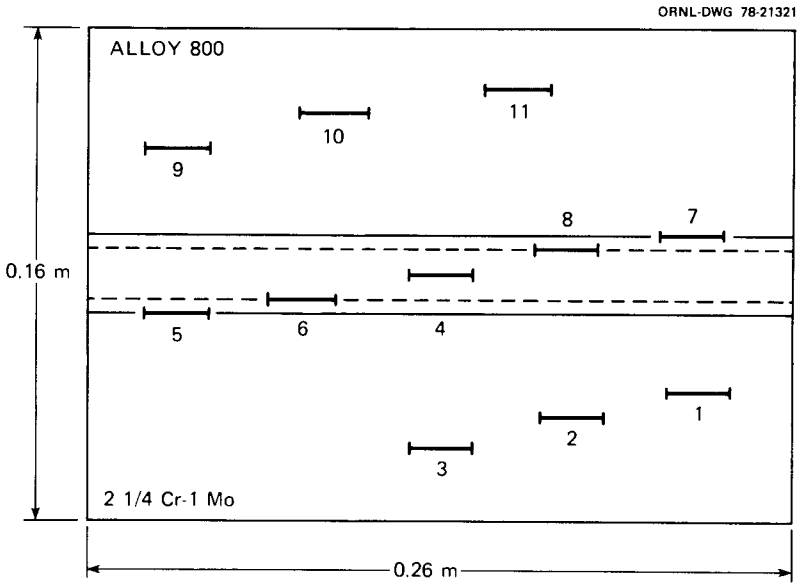

Fig. 16. Weld test sample CR800-12. Weld thickness 15 mm.

Table 6. Description of notches shown in Fig. 16

Notch	Location	Surface	Notch dimensions, mm		
			Depth	Length	Depth (%*T*)
1	Base	Crown	0.8	17.8	5.3
2	Base	Root	0.6	16.0	4.0
3	Base	Crown	0.7	17.1	4.7
4	Weld	Root	1.5	24.9	10.0
5	Interface	Crown	0.8	17.8	5.3
6	Interface	Root	0.7	17.0	4.7
7	Interface	Crown	1.6	25.4	10.7
8	Interface	Root	1.6	25.4	10.7
9	Base	Crown	1.7	25.9	11.3
10	Base	Root	1.5	25.0	10.0
11	Base	Crown	1.7	25.9	11.3

depths of the two interface notches (5 and 6) are approximately 5% of the weld thickness (5%*T*). Figures 17 and 18 show the test results obtained (at different gain settings) when weld test sample CR800-12 was scanned at test frequencies of 1 and 5 MHz. In Fig. 17 we can barely detect the 5%*T* interface notches (5 and 6) at a 1 MHz test frequency, and the signal-to-noise ratio is about 1. Using a 5 MHz test frequency to inspect the same weld (Fig. 18), we can detect both 5%*T* interface notches (5 and 6) at 16 dB greater than the noise level. Also note that no notches or even noise signals are detected from the weld volume at 5 MHz, whereas both root notches 4 and 8 and considerable weld noise were detected at 1 MHz. We also examined this weld at 2.25 MHz and got results that fell between those shown in Figs. 17 and 18. We have been unable to detect any notches in the weld volume at 5 MHz, and we cannot inspect alloy 800 at 5 MHz, but this frequency definitely provides increased test sensitivity and resolution for ultrasonic shear wave inspection at the 2¼ Cr-1 Mo/ERNiCr-3 weld interface when the inspection is conducted from the 2¼ Cr-1 Mo base metal side.

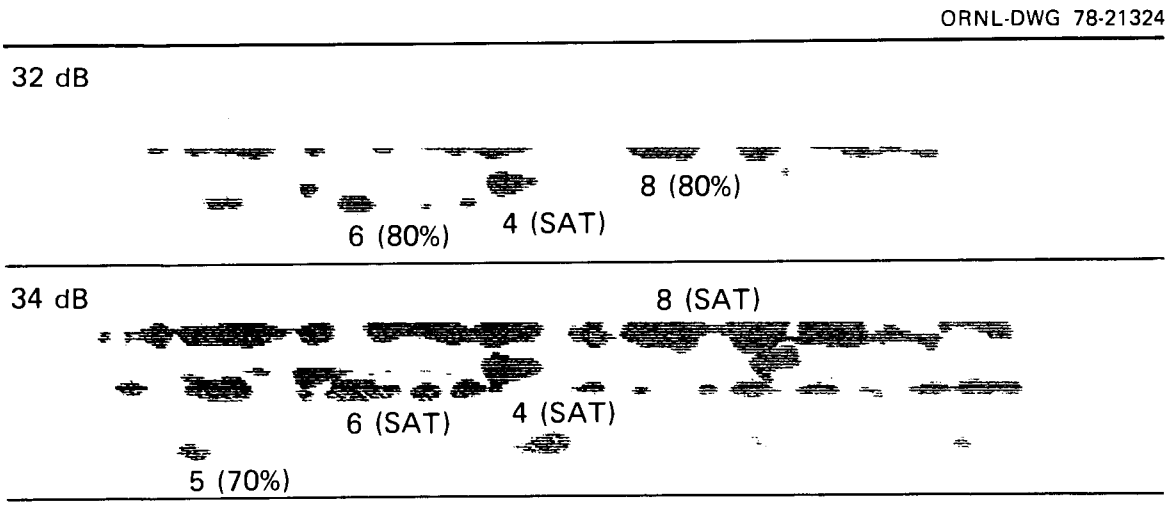

Fig. 17. C-scan results of 1-MHz shear-wave inspection of 5%*T* interface notches in weld sample CR800-12 scanning from 2¼ Cr-1 Mo toward the weld.

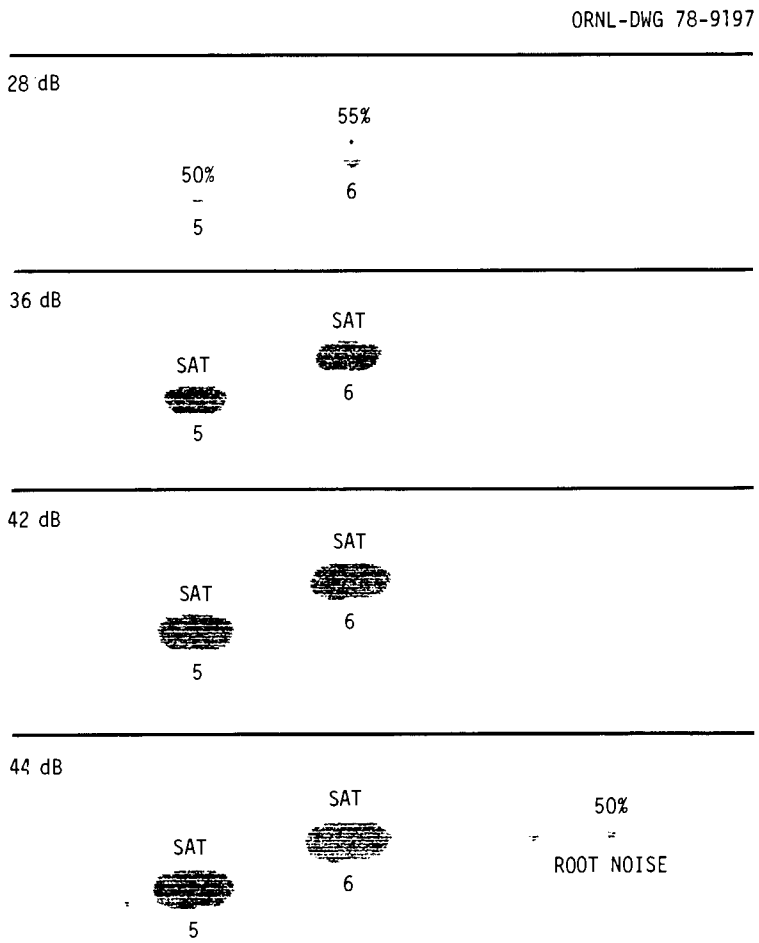

Fig. 18. C-scan results of 5-MHz shear-wave inspection of 5%*T* notches at weld interface scanning from 2¼ Cr-1 Mo base metal in weld sample CR800-12.

Pursuing the ability to obtain improved test sensitivity by using multiple operating frequencies, we placed 0.05-, 0.13-, 0.25-, and 0.37-mm-deep (2, 5, 10, and 15 mil) electrical discharge machined (EDM) notches in the 2¼ Cr-1 Mo base plate of 13-mm-thick weld sample W-12 (Fig. 19, Table 7). These notches are identified as E2, E5, E10b, and E15. We also placed a 0.25-mm-deep (10-mil) EDM notch (E10a) at the root of the 2¼ Cr-1 Mo/ERNiCr-3 weld interface. In addition, this sample contains two 12%*T*-deep saw-cut notches (5 and 6) located at the weld interface.

Figure 20 shows the results obtained when weld sample W-12 was ultrasonically examined with a 5-MHz shear wave technique. We made three scans of the base metal notches at three different instrument gain settings and two scans of the weld interface (from the 2¼ Cr-1 Mo side) at different gain settings.

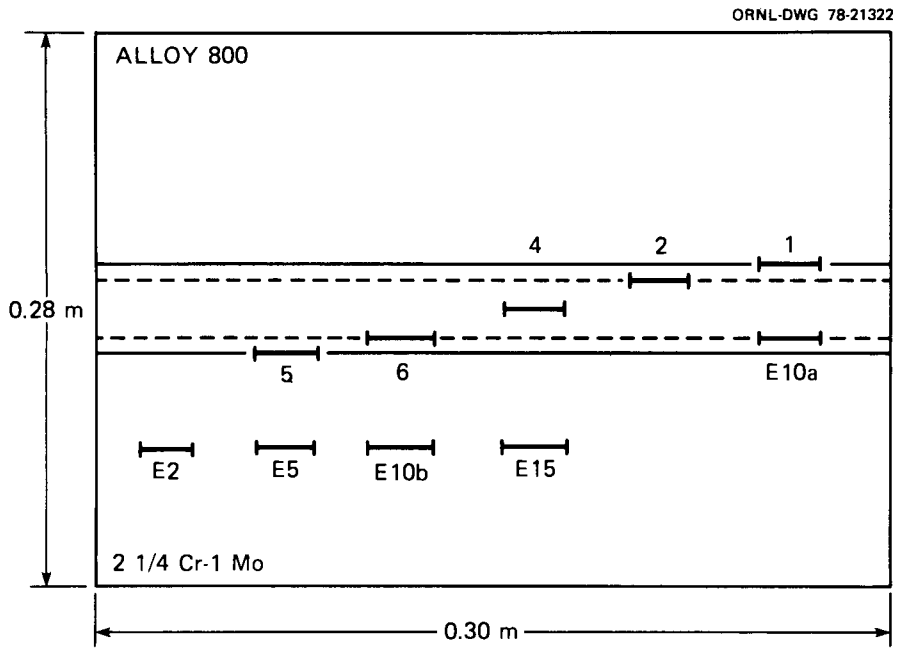

Fig. 19. Weld test sample W-12. Weld thickness 13 mm.

Table 7. Description of notches shown in Fig. 19

Notch	Location	Surface	Notch Dimensions, mm		
			Depth	Length	Depth (%*T*)
1	Interface	Crown	1.45	24.5	11.2
2	Interface	Root	1.52	25.0	11.7
4	Center of weld	Root	1.52	25.0	11.7
5	Interface	Crown	1.55	25.0	11.9
6	Interface	Root	1.57	25.1	12.1
E2	Base	Root	0.05	19.0	0.4
E5	Base	Root	0.13	19.0	1.0
E10a	Interface	Root	0.24	18.5	1.8
E10b	Base	Root	0.25	19.0	1.9
E15	Base	Root	0.37	19.0	2.8

All notches could be detected with 5 MHz; see Fig. 20. The 0.25-mm-deep notch (E10a), located at the root of the near weld interface, was detected approximately 12 dB above the weld noise level (30 dB). The 0.13-mm-deep notch (E5) located in base metal could be detected at 2 dB above the weld noise level (30 dB). The 0.05-mm-deep notch (E2) could be distinctly detected in base metal but would not have been identified if it had been located in the weld because its detection required a gain much higher than the weld noise level. Signals from the other notches were very large and will not be discussed. The weld sample was also examined at other test frequencies, and we could not detect the 0.05-mm-deep notch (E2) at a 1 MHz test frequency. We could barely detect the 0.13-mm-deep notch (E5) using 2.25 MHz. These data provide a relative measure of test resolution for this material and these three frequencies, at least for this particular test arrangement. Note that the depths of the EDM notches are smaller than the wavelength of the shear-wave sound energy for the three frequencies used (refer to Table 3).

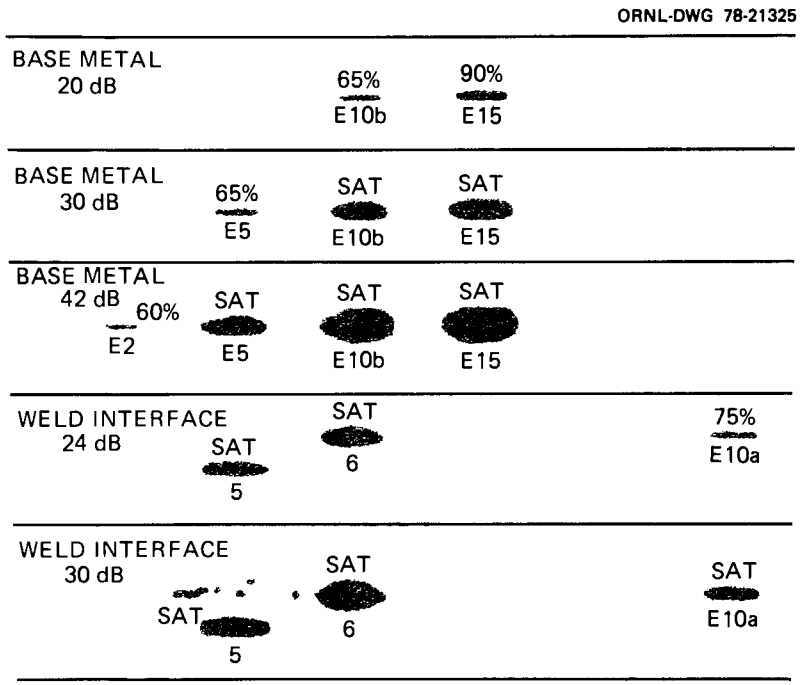

Fig. 20. C-scan results of 5-MHz shear-wave inspection of notches in base metal and at weld interface in weld sample W-12 scanning from 2¼ Cr-1 Mo toward the weld.

These data show that we can detect a 0.05-mm-deep notch in 2¼ Cr-1 Mo base metal. This is a measure of test sensitivity but it relates to base metal only. A notch of this depth could not be detected in the weld or at the weld interface because the weld noise (which begins to record at 30 dB) will completely mask the indication from the notch, which first records at about 40 dB. These data help to illustrate a couple of significant points: (1) base metal reference reflectors make poor calibration standards for weld inspections, and (2) no sensitivity determination can be made for a weld inspection without also considering the weld noise level and determining a signal-to-noise ratio for the reference reflector. We might add that the ability to detect notches of a given size does not necessarily mean that we can detect cracks of similar dimensions. In general, notches (and SDHs) reflect more sound energy than cracks. Notches usually present a planar surface for reflection, and they are generally oriented in an optimum direction for reflection of sound

energy. Cracks, on the other hand, are usually tightly closed near the tips, and this closed portion of a crack can sometimes transmit sound energy, making the cracks appear smaller during an ultrasonic inspection. A correlation between the ultrasonic response from notches, cracks, and SDHs is being investigated at ORNL, and a report will be published in the near future.

To complete this study for the 2¼ Cr-1 Mo/ERNiCr-3 weld interface we examined a 27-mm-thick weld sample (CR800-6), Fig. 21 and Table 8. Using previous data obtained from 13-mm-thick welds as a guideline we placed saw-cut notches whose depths were approximately 8% of the weld thickness at the root and crown surface of both weld interfaces and in the center of the weld root. Even-numbered notches are located on the root surface and odd-numbered notches on the crown surface of the weld sample.

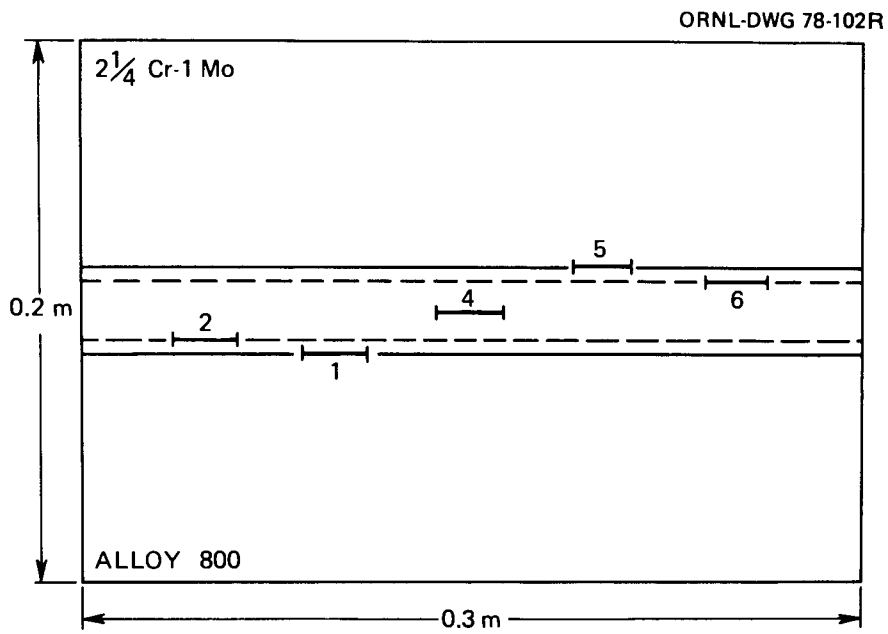

Fig. 21. Weld test sample CR800-6. Weld thickness 27 mm.

Table 8. Description of notches shown in Fig. 21

Notch	Surface	Dimensions, mm		Depth (%*T*)
		Depth	Length	
		Weld CR800-6		
1	Crown	2.24	25.9	8.3
2	Root	2.29	25.8	8.5
4	Root	2.24	25.7	8.3
5	Crown	2.18	25.3	8.1
6	Root	2.21	25.5	8.2

Figure 22 shows the results of scanning weld sample CR800-6 from the 2¼ Cr-1 Mo side of the weld at different gain levels by 1-MHz shear wave techniques. The 8%*T* root and crown weld interface notches 5 and 6 can be detected with at least a 4:1 signal-to-noise ratio (12 dB > noise). Notch 4, which is also 8%*T* and is located in the center of the weld root, can be detected at least 4 dB greater than weld noise.

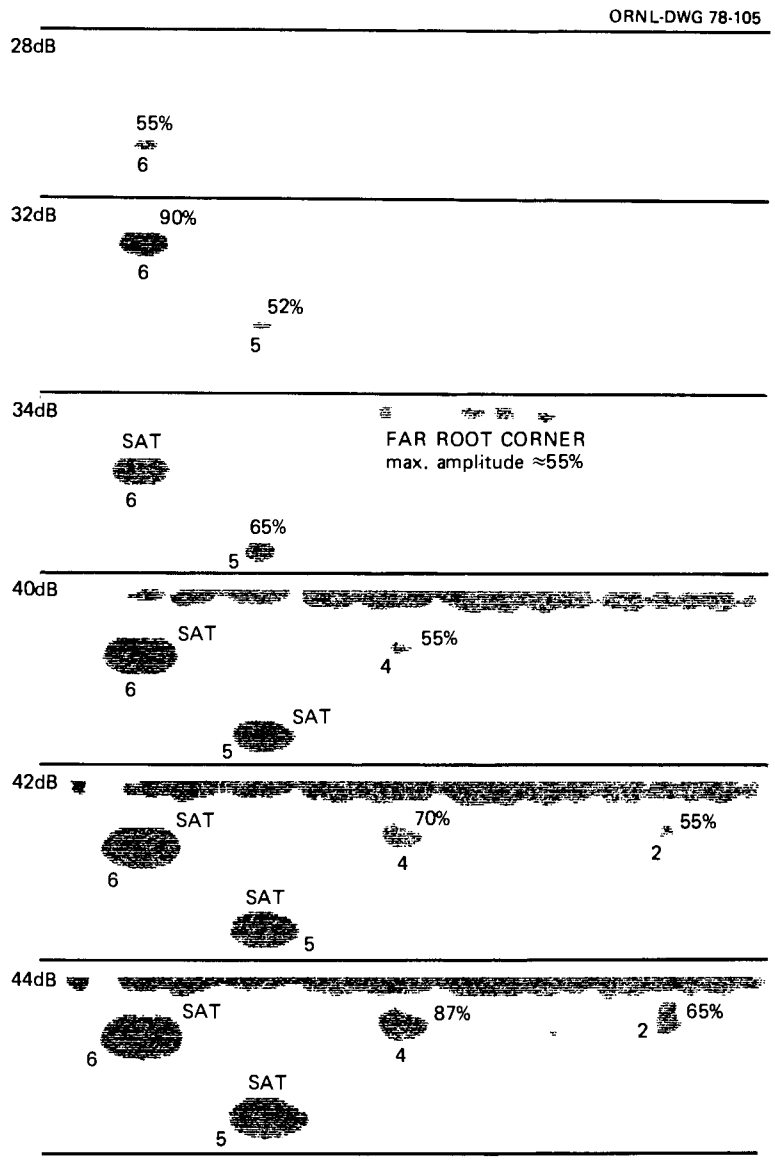

Fig. 22. C-scan results of 1-MHz shear-wave inspection of 27-mm-thick ERNiCr-3 weld CR800-6 from the 2¼ Cr-1 Mo steel side, using filters.

Tests performed at 5 MHz show a slight improvement in the signal-to-noise ratio to 14 dB (about 5:1) for the two weld interface notches (5 and 6). We could not detect notch 4 at 5 MHz. We could not detect notch 2 at 2.25 MHz.

The heavy dark indication at the top of the scans for 34, 40, 42 and 44 dB represents the reflection from the metallurgical corner at the far weld root interface. Similar reflections were obtained from the 13-mm-thick welds and were discussed earlier with Fig. 15. The amplitudes of the signals reflected from weld corners can be quite large and can mask discontinuity indications if they occur in the same time period on the CRT. Notch 2 was supposed to be at the weld-to-alloy-800 root interface, but actually it was placed about 2 mm inside the root interface in the weld metal. This is one reason that the reflected signal from notch 2 is not masked by the corner reflector. We could scan more than halfway across the weld

before recording the corner reflection; therefore, an ultrasonic inspection could be performed on this weld by examining half the weld from one side and the other half from the opposite side of the weld (testing from the crown surface only). We can easily omit this reflection from the final data by simply stopping the recording (after obtaining the signal from notch #2) before the signal occurs, see Fig. 23. The signal is still present on the CRT but we just did not record it. This essentially is what an operator must do mentally and on the spot when he performs an ultrasonic weld inspection by observing the oscilloscope and writing down the test results. The ability to record the raw data from an ultrasonic weld inspection on magnetic tape could significantly improve data interpretation because it would provide the opportunity to go over the data as many times as desired and to analyze and evaluate the data in any manner possible to confirm whether the signals are noise or are true flaw indications.

In comparing the test results in Figs. 22 and 23 note that the instrument gain settings (on the left hand sides of the figures) are distinctly different. The data in Fig. 22 were obtained using filters on the ultrasonic instrument. These filters apparently reduce noise signals and give the discontinuity indications a more symmetrical appearance on the oscilloscope. The data in Fig. 23 were obtained without filters. There is little difference between the data in the two figures (ignoring the fact that the reflection from the far root corner was arbitrarily omitted in Fig. 23). We compared other weld test data obtained with and without the use of filters and the results were similar. Our conclusions were that filters offered no improvement

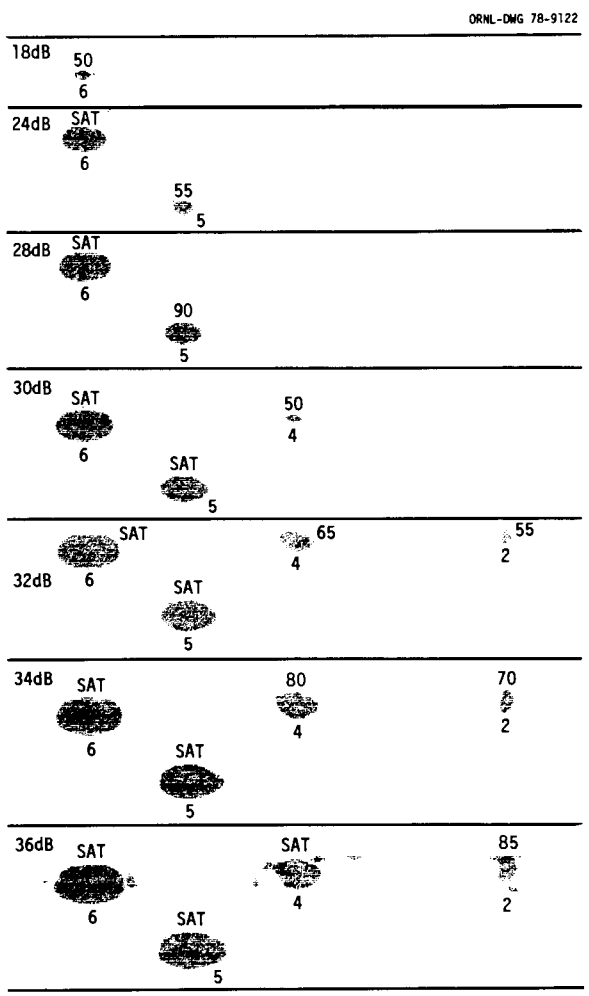

Fig. 23. C-scan results of 1-MHz shear-wave inspection of 27-mm-thick ERNiCr-3 weld (CR800-6) from the 2¼ Cr-1 Mo steel side with no filters and with the scan halted before reaching the corner reflection.

whatsoever for the interpretation of recorded weld test data for this experiment. The use of filters provided a more aesthetic presentation on the oscilloscope at the price of requiring more instrument receiver gain and making the CRT vertical scale less linear. We did not use filters or the reject control for any of the other data shown in this report.

To summarize the results of this investigation to develop an ultrasonic inspection for the 2¼ Cr-1 Mo/ERNiCr-3 weld interface, we have shown that shear-wave techniques can be applied and that different operating frequencies are required for optimum test sensitivity and resolution. Using these methods a 2%*T*-deep notch located at the weld root interface can be detected above the weld noise level, and 5%*T*-deep notches located at both root and crown of the weld interface can be detected with a 6:1 signal-to-noise ratio in 13-mm-thick welds. Notches 8%*T* deep at both the root and crown of the weld interface in the 27-mm-thick weld sample can be detected at a 4:1 signal-to-noise ratio. We can detect 8%*T*-deep notches in the ERNiCr-3 weld root volume at a nominal 2:1 signal-to-noise ratio for either the 13-mm- or 27-mm-thick welds. The optimum test frequency for the 2¼ Cr-1 Mo/ERNiCr-3 weld interface is 5 MHz, and 1 MHz works best for the ERNiCr-3 weld root volume inspection.

Weld Interface of Type 316 Stainless Steel and 16-8-2 Weld Metal

Figure 24 shows a 13-mm-thick weld sample (S800-26) that represents the type 316 stainless steel/16-8-2/alloy 800 transition joint weld. This weld sample was fabricated by the General Electric Company using the techniques described earlier in this report. The root and crown surfaces of the weld were ground flat and smooth to represent in-service conditions. The depths of all notches are approximately 12% of the weld thickness (see Table 9). Saw-cut notches were placed on the root and crown surfaces of both base metals, both weld interfaces, and the weld itself. Even-numbered notches are on the root surface and odd numbered notches are on the crown surface of the weld sample.

Figure 25 shows the results obtained when this sample was ultrasonically inspected from the type 316 stainless steel side by a single-transducer 45° shear-wave immersion technique at a test frequency of 1 MHz. The tests were performed at different gain settings, and the transducer was indexed completely across the weld. The testing techniques and scanning procedures described earlier in this report were followed. Gain settings were selected according to the techniques described earlier. Note that notches 3, 4, and 6 were detected at least 6 dB above the typical weld noise level. This means that we can detect these notches with better than a 2:1 signal-to-noise (S/N) ratio. The indication from notch 8 stands out distinctly above the noise level and approximates a 2:1 S/N ratio. The ability to easily detect notches 3 and 4 indicates good test sensitivity at the near weld interface, and the ability to readily detect root notches 4, 6, and 8 shows a capability to inspect the weld root volume. Notch 5 in the center of the weld crown and notch 7 at the crown of the far weld interface could not be detected distinctly above noise level during these tests. Ultrasonic studies at ORNL on a separate program have shown that considerably deeper notches are required at these locations to obtain distinct reflected signals. We conclude, therefore, that we have a rather poor test sensitivity for the crown volume area of the weld using either a single-transducer shear-wave or a dual-transducer longitudinal-wave technique. On the other hand, experience has shown that the crown volume area is probably the least critical area of the weld as far as inspection requirements are concerned.

As was shown earlier for the results obtained at the 2¼ Cr-1 Mo/ERNiCr-3 weld interface, we can obtain better signal-to-noise ratios for the interface notches by using a higher operating frequency. Figure 26 shows the results of scanning the 16-8-2 weld in sample S800-26 from the type 316 stainless steel side using a 2.25 MHz test frequency. A comparison of the data in Figs. 25 and 26 provides good illustrations of the effects of using different frequencies to inspect austenitic stainless steel welds. Interface notches 3 and 4 can be detected with a slightly improved S/N ratio at 2.25 MHz. This improvement would be more

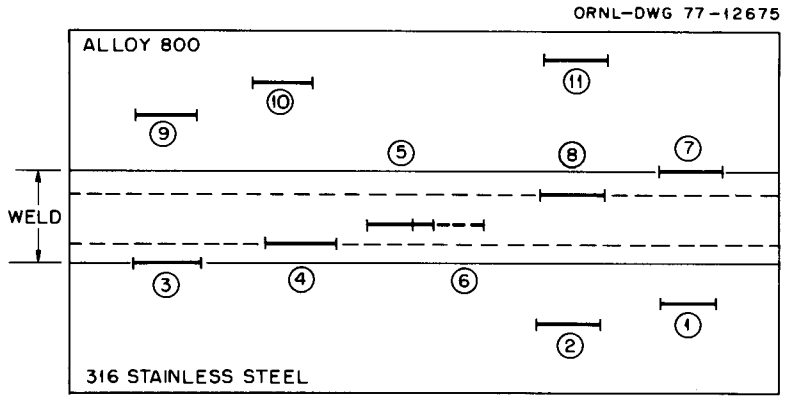

Fig. 24. Weld test sample S800-26. Weld thickness 13 mm.

Table 9. Description of notches shown in Fig. 24

Notch	Surface	Depth (mm)	Length (mm)	Depth (%*T*)
1	Crown	1.6	25.4	12.3
2	Root	1.6	25.4	12.3
3	Crown	1.7	26.0	13.1
4	Root	1.6	25.4	12.3
5	Crown	1.5	24.9	11.5
6	Root	1.5	24.9	11.5
7	Crown	1.5	24.8	11.5
8	Root	1.5	24.9	11.5
9	Crown	1.6	25.4	12.3
10	Root	1.5	24.9	11.5
11	Crown	1.5	24.9	11.5

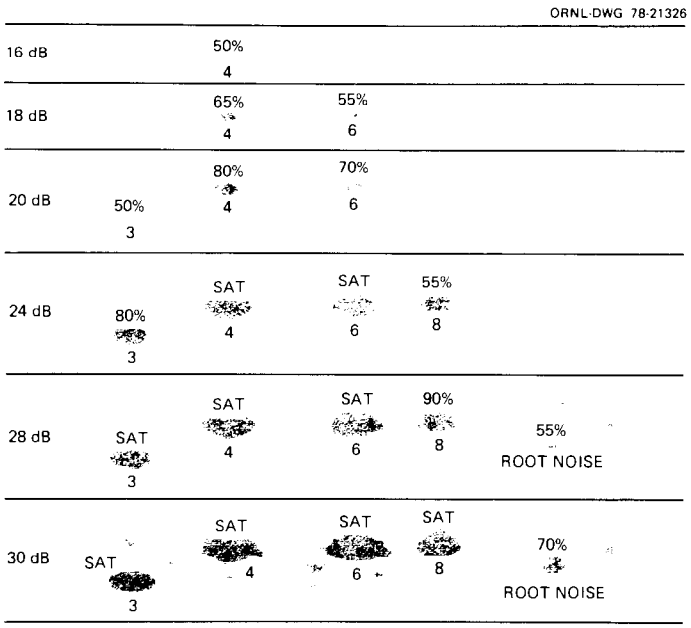

Fig. 25. C-scan results of 1-MHz shear-wave inspection of 13-mm-thick type 16-8-2 weld (S800-26) from the type 316 stainless steel side.

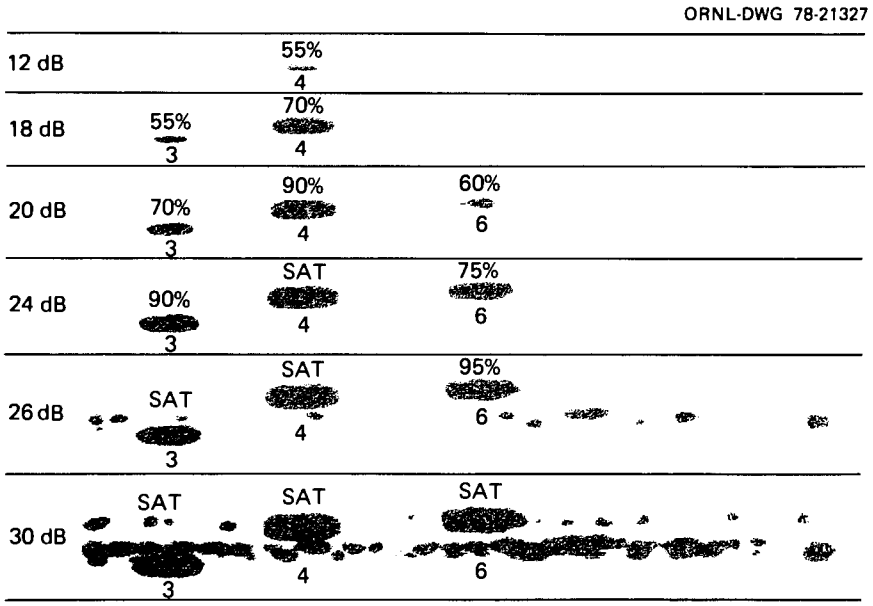

Fig. 26. C-scan results of 2.25 MHz shear-wave inspection of weld sample S800-26 scanning from type 316 stainless steel toward the weld.

significant for smaller notches (5%*T* deep or smaller) because the improvement is primarily a function of wavelength. On the other hand, the smaller wavelength (2.25 MHz) does not penetrate the austenitic weld metal nearly as well, and notch 8 cannot be detected from the type 316 stainless steel side of the weld at 2.25 MHz. Notch 6 in the center of the weld root can be detected slightly better at 1 MHz. We also tried 5 MHz test frequency for this weld interface inspection and found that the results vary with different heats of type 316 stainless steel base metal. This variation can be significant; therefore, we do not recommend using a 5 MHz test frequency to inspect the 316 stainless steel/16-8-2 weld interface except on an individualized weld basis, where the system is recalibrated and transfer methods are applied for each separate piece of base metal encountered.

Figure 27 shows weld sample S800-6, which is 29 mm thick and represents the type 316 stainless steel/16-8-2/alloy 800 transition joint weld for 660-mm-diam pipes. The faces of the weld sample have been ground flat, and circular-saw-cut notches have been placed at the root and crown of both weld interfaces and in the center of the root of the weld. Even-numbered notches are located on the root surface and odd-numbered on the crown surface of the sample. The depths of all notches are approximately 8% of the weld thickness. These notches are described in Table 10.

Figure 28 shows the results of scanning this weld from the stainless steel side at several different instrument gain settings using a single-transducer, 1-MHz, shear-wave immersion ultrasonic inspection technique. All notches, both at the near weld interface and in the weld root volume, can be detected with at least a 2:1 signal-to-noise ratio. Comparing the data in Fig. 28 with that in Fig. 23, we can see that the ERNiCr-3 weld is slightly more attenuative than the 16-8-2 weld, at least for these two samples. This is best indicated by the amplitudes of the reflected signals from notch 4 in each weld. The notches are approximately the same size, and both are located in the center of the weld roots. Notch 4 in sample S800-6 can be seen at much less gain than notch 4 in sample CR800-6. The two interface notches (5 and 6) on the other hand have quite similar amplitudes at the same gain settings. It is also interesting to note that no reflected

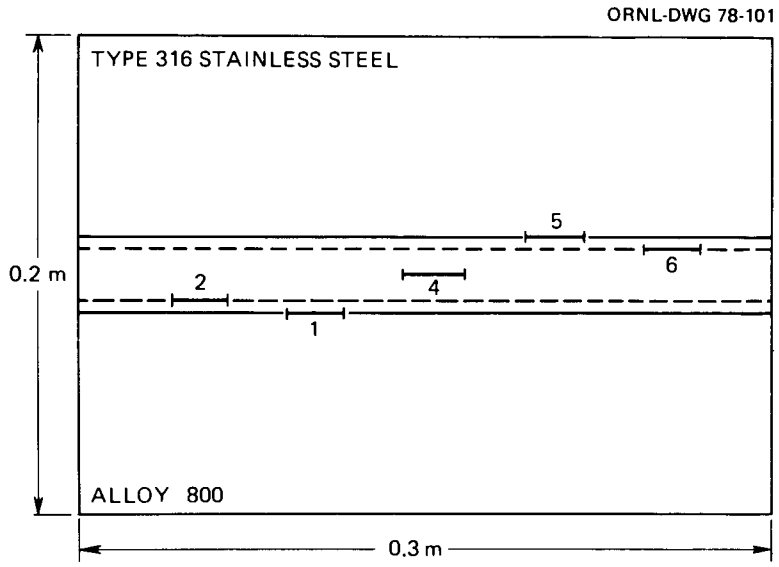

Fig. 27. Weld test sample S800-6. Weld thickness 29 mm.

Table 10. Description of notches shown in Fig. 27 for Weld S800-6

Notch	Surface	Dimensions, mm		Depth (%*T*)
		Depth	Length	
1	Crown	2.24	25.6	7.7
2	Root	2.21	25.5	7.6
4	Root	2.24	25.6	7.7
5	Crown	2.18	25.4	7.5
6	Root	2.18	25.4	7.5

signals were obtained from the far root corner of this weld (for the gain levels examined), such as were recorded from the ERNiCr-3 weld (refer to Fig. 22).

In summary, we found that the type 316 stainless steel/16-8-2 weld interface and the 16-8-2 weld root volume can be ultrasonically inspected with about the same confidence level as the 2¼ Cr-1 Mo/ERNiCr-3 weld interface and the ERNiCr-3 weld root volume when the tests are conducted from the type 316 stainless steel and 2¼ Cr-1 Mo sides of the welds. We obtained slightly better test sensitivity for the 16-8-2 weld root volume. A 1 MHz test frequency provides better test results for the weld root volume inspection and 2.25 MHz worked best for the 316 stainless steel/16-8-2 weld interface inspection.

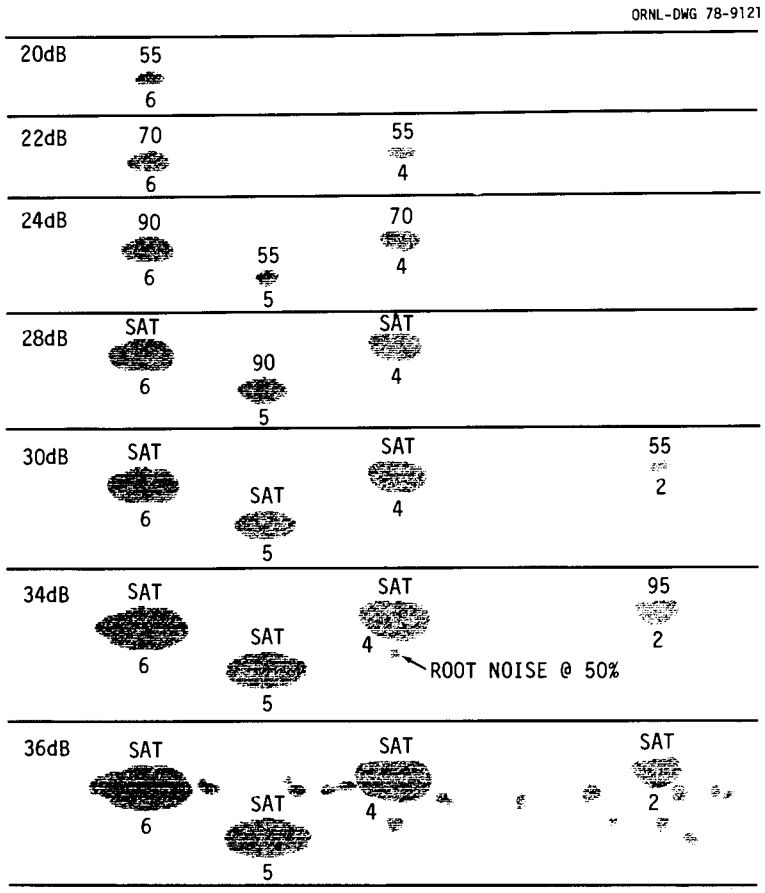

Fig. 28. C-scan results of 1-MHz shear-wave inspection of 29-mm-thick type 16-8-2 weld S800-6 from the type 316 stainless steel side.

Weld Interfaces with Alloy 800

Alloy 800 is a corrosion-resistant, iron-nickel-chromium alloy. It has an austenitic structure and is highly attenuative to ultrasonic energy for frequencies of 2.25 MHz and higher, as was discussed earlier in this report. This material is practically opaque to shear-wave sound energy at 2.25 and 5 MHz. Using 2.25 MHz we could detect in a-13-mm-thick base plate root notches whose depths were about 10% of the plate thickness when the sound wave traveled a ½ V-path to impinge on the notch. We could not detect 10%T notches on the crown surface using 2.25 MHz shear wave techniques when the sound energy traveled a full V-path. Similar results were obtained by dual longitudinal-wave techniques at 2.25 MHz. We could detect 10%T notches on the root surface in alloy 800 base metal, and the reflected signal had a greater amplitude than that for shear waves at the same frequency, but we could not routinely detect 10%T notches on the crown surface, where the sound traveled a full V-path (this may have been due to our inability to bounce focus the two beams). We also tried single-transducer longitudinal wave techniques and were still unable to distinctly detect 10%T crown notches in 13-mm-thick alloy 800 when the sound had to travel a full V-path to impinge on the notches. We found that by using a 1-MHz shear wave technique we could obtain fairly good test sensitivity so all the following data for the inspection of either of the two transition joint welds from the alloy 800 side of the weld were obtained at a 1 MHz test frequency by 45° shear-wave immersion techniques.

All data shown for the alloy 800 weld interfaces were obtained by inspecting the same weld test samples already discussed for the previous two transition joint weld interfaces (2¼ Cr-1 Mo/ERNiCr-3 and type 316 stainless steel/16-8-2). We merely inspected the other side of the weld (from the crown surface) with the sound beam incident on the alloy 800 base plate.

Alloy 800/16-8-2 Weld Interface

Figure 29 shows the results of ultrasonically inspecting the 13-mm-thick type 16-8-2 transition joint weld test sample S800-26 (Fig. 24) from each base metal side of the weld using a 1-MHz shear-wave technique. The sound beam was always incident on the crown surface of the weld sample, and the same instrument gain setting was used for all scans. The depths of all of the notches are approximately 12% of the weld thickness. We did not detect notch 9 in the data shown in Fig. 29(a) because it was too close to the weld, and the weld crown blocked and dispersed the incident sound beam. For this reason, notch 11 was placed in the sample to show the ability to detect a 10%T deep crown notch in alloy 800 when the sound travels a full V-path. Note that the indications for notches 7 and 11 are relatively small in Fig. 29. This is the result of the longer path of the sound beam in the highly attenuating alloy 800. Also note that

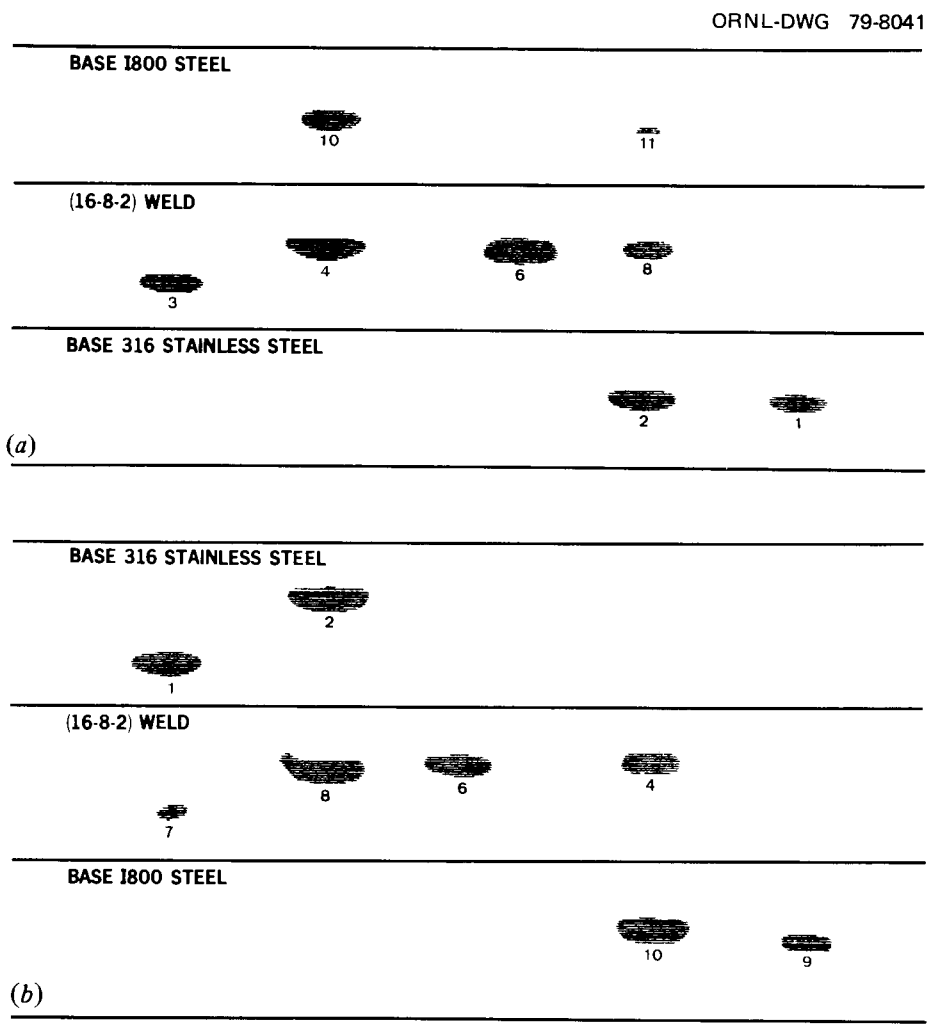

Fig. 29. C-scan results of 1-MHz single-transducer shear-wave inspection of weld sample S800-26 when scanning: (a) From type 316 stainless steel toward alloy 800 and (b) from alloy 800 toward type 316 stainless steel.

no noise was recorded on either scan as the sound beam was indexed completely across the sample. All root notches were easily detected. This data indicates a test capability, at least for 13-mm-thick welds.

Figure 30 shows ultrasonic data recorded from weld test sample S800-26 (Fig. 24) at several different instrument gain settings and scanned only from the alloy 800 side of the weld. Note that all weld root volume notches (4, 6, and 8) can be detected at a lower gain setting than the crown notch (7) at the alloy 800 weld interface. This is another example of the high attenuation by alloy 800. All the notches (weld interface and weld root volume) can be detected at least 6 dB greater than the weld noise level (30 db); therefore, all notches can be detected with a signal-to-noise ratio of at least 2.

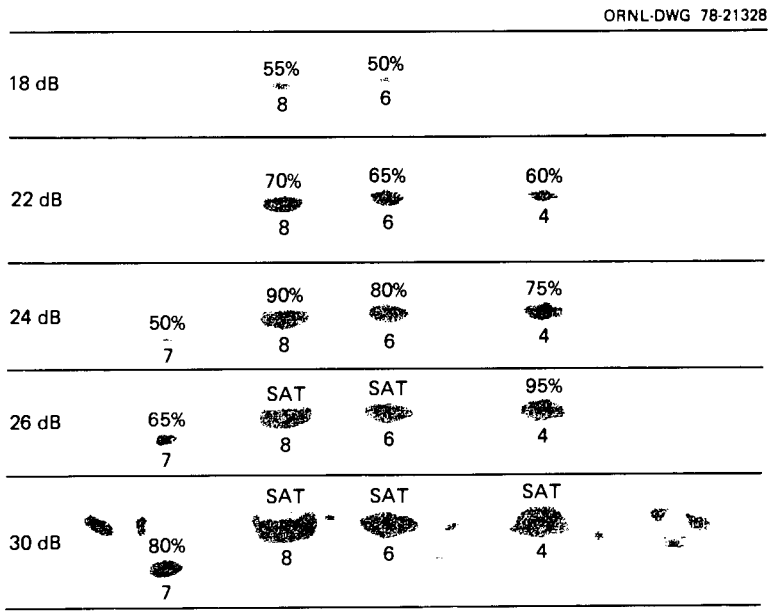

Fig. 30. C-scan results of 1-MHz shear-wave inspection of 13-mm-thick weld sample S800-26 scanning from the alloy 800 toward the type 16-8-2 weld.

Because of the high attenuation of alloy 800 and the results obtained from 13-mm-thick transition joint weld samples, we were concerned that we might not be able to inspect weld samples from the alloy 800 side when the weld thickness was doubled to 26 mm. Figure 31 shows the results of several 1-MHz ultrasonic shear-wave inspections of 29-mm-thick weld test sample S800-6 (Fig. 27) from the alloy 800 side of the weld using different instrument gain settings. All root notches (weld root volume) can be detected at a nominal 2:1 signal-to-noise ratio, but notch 1 at the near weld crown interface can not be detected significantly greater than the weld noise level (38–40 dB). As we were conducting these tests we noted that most of the noise was coming from the root area of the weld. We applied special gating techniques as described earlier to eliminate those signals coming from the root area of the weld, and to accept and record only those signals reflected from the crown area of the weld. We then repeated the previous tests, and the results are shown in Fig. 32. Utilizing this modification in our testing technique we can easily obtain a 2:1 signal-to-noise ratio for the interface crown notch 1.

All data discussed in this report before Fig. 32 were obtained with our ultrasonic gate used primarily as an amplitude control. The height of the gate was set so that only those signals that exceeded 50% amplitude on the oscilloscope were recorded. The width of the gate was set to cover the full weld width from root to

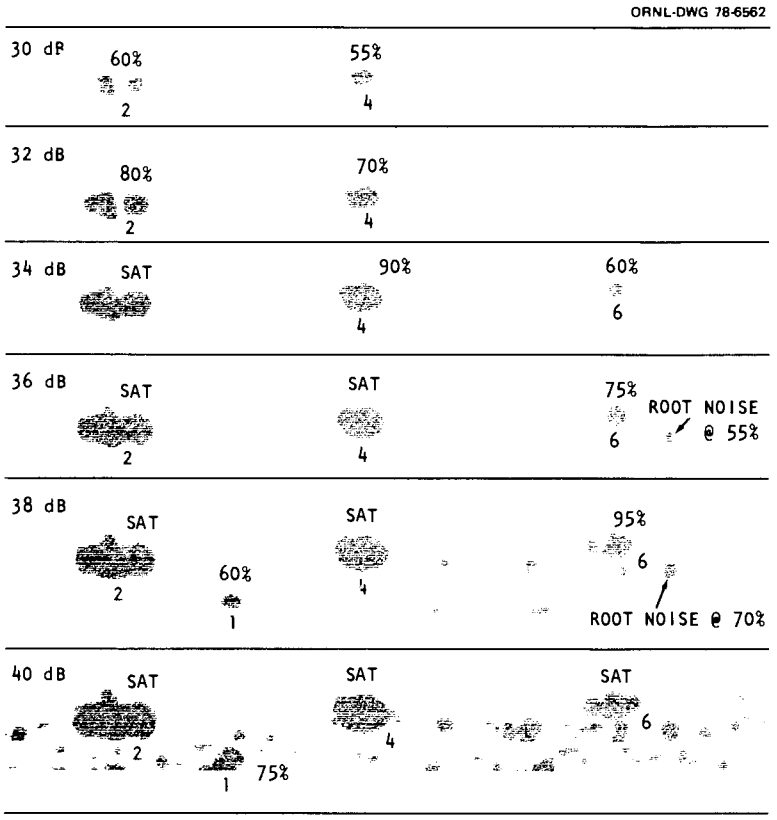

Fig. 31. C-scan results of 1-MHz shear-wave inspection of weld sample S800-6 scanning from alloy 800 toward the weld (wide gate).

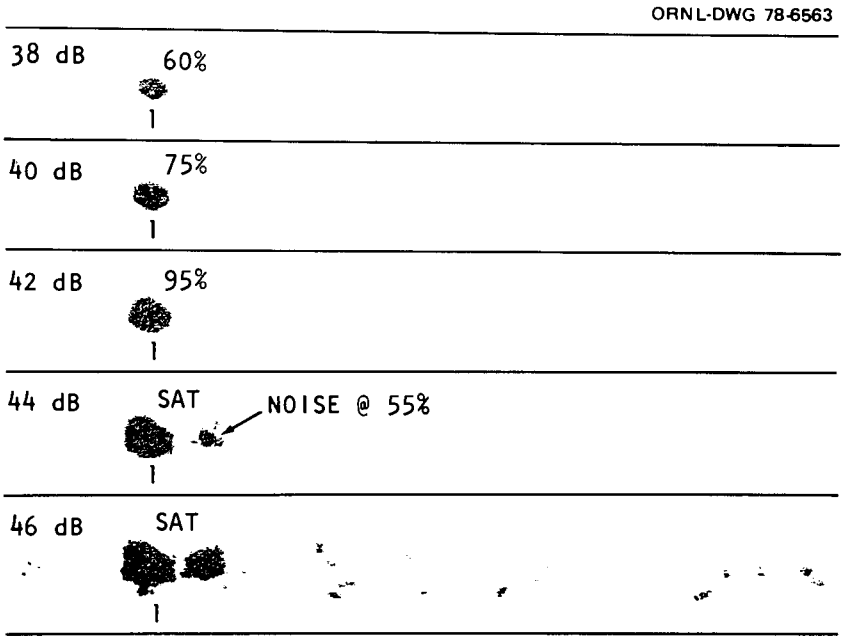

Fig. 32. C-scan results of 1-MHz shear-wave inspection of weld sample S800-6 scanning from alloy 800 toward the weld (gated crown only).

crown. In some special cases we adjusted the start of the gate to eliminate obvious surface irregularities (on the crown surface only).

We used dual gates to make the gating corrections required to obtain the data shown in Figs. 31 and 32. One was set to record any signal reflected from the full width of the weld. The other gate was set to record only those signals reflected from the upper half or crown half of the weld. Both gates were set to record only those signals that exceeded 50% amplitude on the ultrasonic scope. The outputs from the two gates were recorded independently. If only one gate is available on the UT instrument, the same correction can be made, but two independent scans of the weld are required.

Another technique that can be used to correct for the above-mentioned problem is to apply distance-amplitude corrections (DAC). None of the previous data discussed in this report have had distance-amplitude corrections applied; we recorded the various signals as they occurred assuming that any corrections or modifications that should be made could be applied at a later date. We experienced no problems using these techniques until we began inspecting from the alloy 800 side of the welds. The first difficulty was encountered when the sound beam traveled a full V-path in the alloy 800 base plate and the problem became more distinct when the weld thickness was increased to 29 mm.

Partial distance-amplitude corrections were made for the ultrasonic tests of weld sample S800-6 by setting our two gates to record only signals reflected respectively from the root half and crown half of the weld thickness. We then adjusted the gate level controls to allow the crown gate to record signals having approximately 6 dB lower amplitude than the root gate similar to the photo in Fig. 9(a). The outputs of both gates were fed to the same pen on the C-scan recorder and the results were recorded on a single scan of the weld. (The difference in time between signals from the crown and root area of the 29-mm-thick weld prevented any cross-talk or interference between the recorded signals.) The results of this inspection are shown in Fig. 33 for three different instrument gain settings. All notches at the weld interface and in the

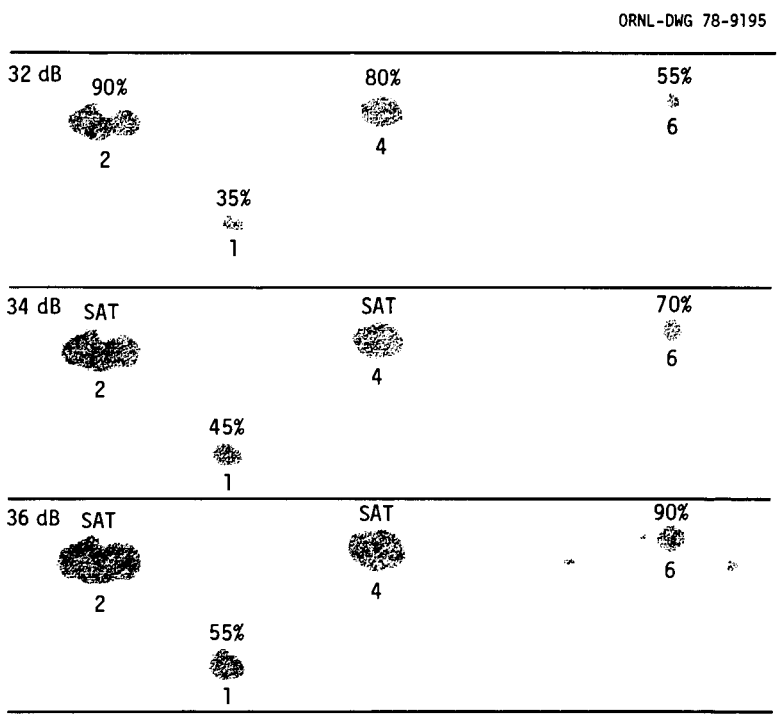

Fig. 33. Results of 1-MHz shear-wave C-scan inspection of 29-mm-thick type 16-8-2 weld from the alloy 800 side using distance-amplitude correction.

weld root volume can be distinctly detected on all three scans. This technique requires some special instrumentation (the ability to record from two separate gates), but this feature is available on commercial ultrasonic equipment. The same results can be obtained if the data are recorded and processed by a computer.

Actually, a full distance-amplitude correction was not made for the data in Fig. 33. The correction should have been 8 dB to equate the amplitudes of the reflected signals from notches 1 and 2; see Fig. 31. When the linear range of conventional ultrasonic equipment is considered, along with the typical noise reflected during a weld inspection, a distance-amplitude correction of 8 dB is feasible, but any correction greater than 6 dB is not very practical. A complete distance-amplitude correction becomes even more of a problem with the alloy 800/ERNiCr-3 weld interface.

Alloy 800/ERNiCr-3 Weld Interface

Figure 34 shows the results obtained when 13-mm-thick weld test sample CR800-12A (Fig. 14) was ultrasonically inspected from the alloy 800 side of the weld using a 1-MHz shear-wave technique at several different instrument gain settings. These data show that we can detect 10%*T* notches at the weld interface and in the center of the weld root with a 2:1 signal-to-noise ratio.

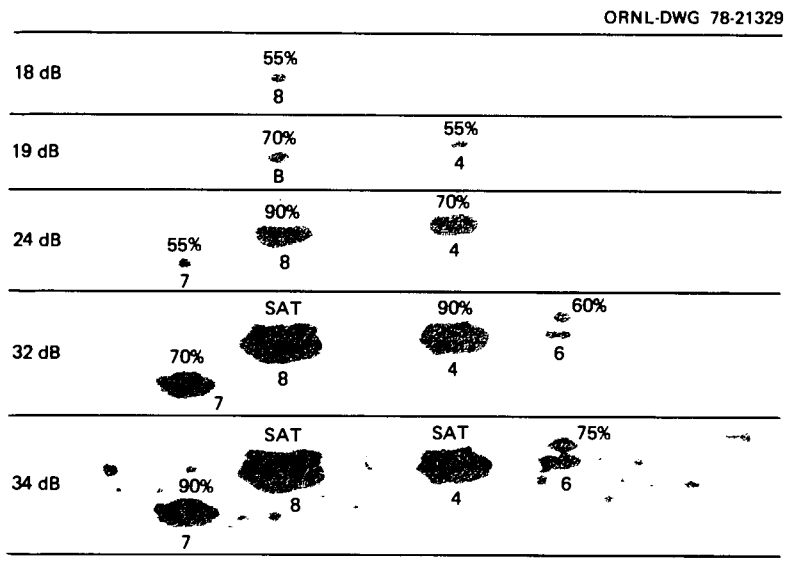

Fig. 34. C-scan results of 1-MHz shear-wave inspection of weld sample CR800-12A scanning from alloy 800 toward the weld.

Comparing the data in Fig. 34 with Fig. 30 shows obvious acoustical differences between the two welds and alloy 800 weld interfaces. For example, the noise level is lower (more gain is required) for the alloy 800/ERNiCr-3 weld interface, and the ERNiCr-3 weld attenuates sound energy more than the 16-8-2 weld. The increased attenuation is illuminated by the fact that notch 6 at the far root interface is more difficult to detect through the ERNiCr-3 weld. Similar differences in attenuation can be noted by comparing Figs. 15 and 25, where the welds were inspected from the 2¼ Cr-1 Mo steel and type 316 stainless steel slides.

The acoustical differences between the two welds were even more evident when we inspected the 27-mm-thick weld sample, CR800-6 (Fig. 21), from the alloy 800 side. The data are shown in Fig. 35. We were unable to detect the 8%*T* notch 6 in the far weld root interface (we also tried longitudinal-wave

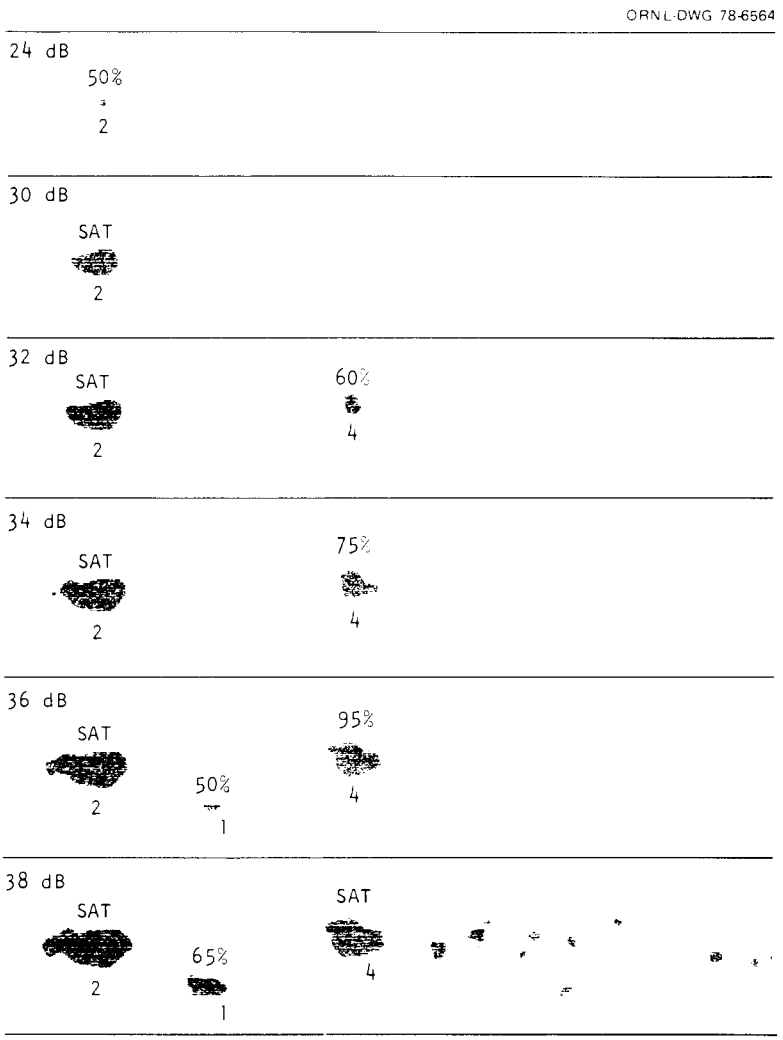

Fig. 35. C-scan results of 1-MHz shear-wave inspection of weld sample CR800-6 scanning from alloy 800 toward the weld (wide gate).

techniques). Notch 4 in the center of the weld root could be detected at a 2:1 signal-to-noise ratio. We could also detect all weld root notches at a 2:1 signal-to-noise ratio when we inspected from the 2¼ Cr-1 Mo side of the ERNiCr-3 weld; see Fig. 23. Considering this information, we assume that if we inspect the ERNiCr-3 weld from both interface sides, we should have good test sensitivity for the root volume area of the weld.

We experienced the same difficulty in detecting the weld crown interface notch 1 as we did with the alloy 800/16-8-2 weld interface (see Fig. 31). The solution also was the same; we gated only the crown area of the weld and omitted signals reflected from the weld root area to obtain the data shown in Fig. 36. These data show that both weld interface notches can be detected at better than a 3:1 signal-to-noise ratio.

As seen from Fig. 35, a distance-amplitude correction of 12 dB is required to equate the amplitudes of notches 1 and 2. This would be impractical to do manually on the oscilloscope, or even electronically by the ultrasonic instrument. One solution would be to inspect each area independently at different instrument gains. Probably the best solution to distance-amplitude correction problems such as these (and also

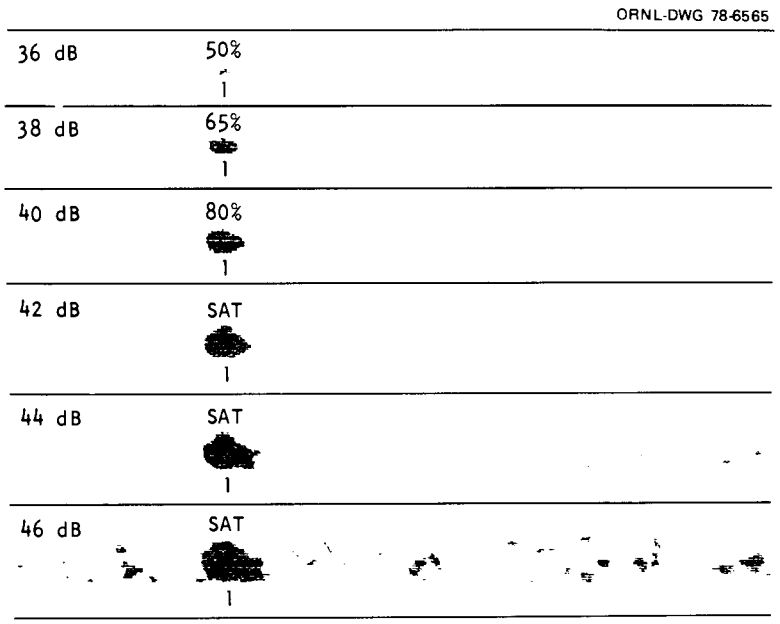

Fig. 36. C-scan results of 1-MHz shear-wave inspection of weld sample CR800-6 scanning from alloy 800 toward the weld (gated crown only).

many other problems) would be to record the results of the ultrasonic test in its raw signal form on tape and then analyze the data with the aid of electronic equipment such as wave analyzers and digital computers. Another feature for this approach is that the raw ultrasonic data can be maintained intact in its original form for future reference.

CONCLUSIONS AND RECOMMENDATIONS

We examined the acoustical properties involved and measured significant differences in shear velocity with respect to the direction of propagation in the austenitic weldments. We investigated attenuation in the materials and found that alloy 800 has a very high attenuation to sound energy at 2.25 MHz and higher frequencies, but this material can be inspected with a 1 MHz test frequency. We examined several different ultrasonic test methods and selected the one that best fit the overall problem (shear-wave techniques). We then optimized the various test parameters such as frequency, transducer size and type, and inspection angle. The results showed that a 13-mm-diam, narrow-band, flat transducer produced optimum results for the weld inspections discussed in this report. A single-transducer 45° shear-wave technique can be used to inspect the four weld interfaces and weld root volume of the two welds in the CRBR dissimilar-metal transition joint, at least for inspections of 13- and 26-mm-thick welds in the as-manufactured condition. We found that the optimum test frequency depends on several factors, such as the attenuation properties of the base metal and the particular area of the weld being inspected. For example, the attenuation properties of alloy 800, which are primarily related to grain size, require that a 1 MHz test frequency be used to inspect the weld and weld interface through this material. The longer wavelength of the 1 MHz frequency is required for a significant amount of sound energy to traverse alloy 800 in the thickness ranges examined in this report.

The ability to detect 8%*T*-deep notches at different areas in the transition joint welds with 1, 2.25, and 5 MHz test frequencies is summarized in Table 11. We can routinely detect with a 2:1 signal-to-noise ratio

Table 11. Ability to detect 8%*T* notches distinctly above noise level in transition joint welds

Inspection surface	Test frequency (MHz)	Detection at each notch location				
		Near weld interface		Center of weld root width	Far weld interface	
		Root	Crown		Root	Crown
2¼ Cr-1 Mo ERNiCr-3 Alloy 800 Weld Joint						
2¼ Cr-1 Mo	1	yes	yes	yes	yes	no
2¼ Cr-1 Mo	2.25	yes	yes	yes	no	no
2¼ Cr-1 Mo	5	yes	yes	no	no	no
Alloy 800	1	yes	yes	yes	no	no
Alloy 800	2.25	no	no	no	no	no
Alloy 800	5	no	no	no	no	no
Type 316 SS/16-8-2/Alloy 800 Weld Joint						
Alloy 800	1	yes	yes	yes	yes	no
Alloy 800	2.25	no	no	no	no	no
Alloy 800	5	no	no	no	no	no
Type 316 SS	1	yes	yes	yes	yes	no
Type 316 SS	2.25	yes	yes	yes	no	no
Type 316 SS	5	yes	yes	no	no	no

notches whose depths are 8% of the weld thickness at any of the four weld root interfaces and in the weld root volume of both welds. Better sensitivity can be obtained if multiple test frequencies are used and if only the root areas of the welds and weld interfaces are considered.

Using the results of these studies, we have developed ultrasonic inspection methods that can be used to evaluate 12.7- and 25.4-mm-thick dissimilar-metal welds in transition joints in the as-manufactured (machined) condition. We have shown that distance-amplitude corrections will be required for an optimum inspection of the transition joint welds. These corrections can be accomplished several ways, but we recommend that the ultrasonic data be recorded on magnetic tape or by some comparable technique so that data analysis and corrections can be programmed and the base data will be available for future reference.

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