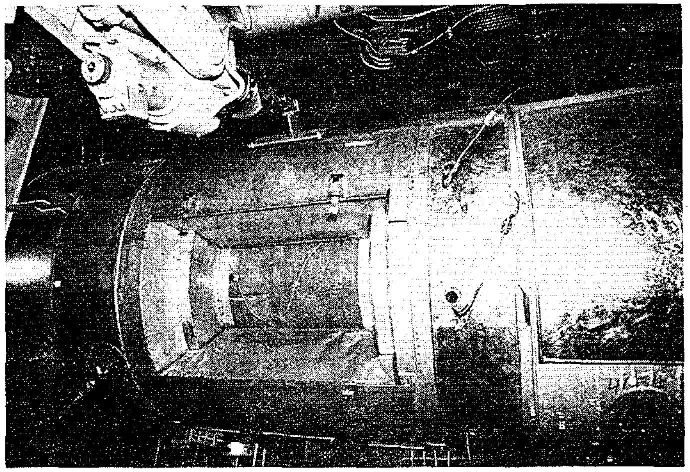


FIG. 12.

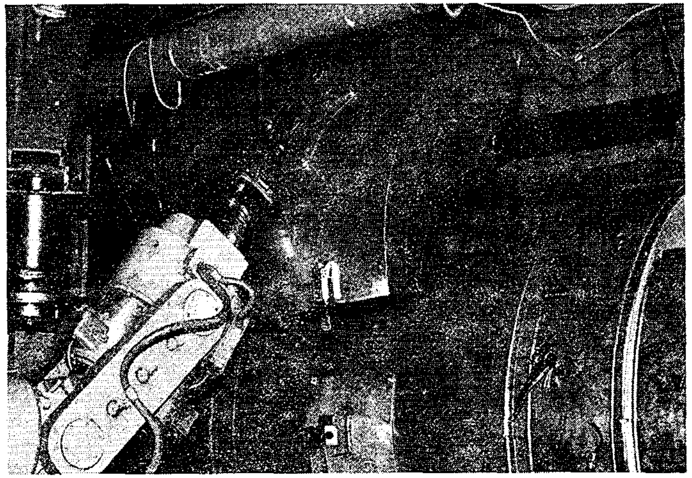


FIG. 13.

LONGITUDINAL WAVE ULTRASONIC INSPECTION OF AUSTENITIC WELDMENTS

B. S. GRAY, R. J. HUDGELL, H. SEED
RNL, UKAEA,
Risley, Warrington, Cheshire,
United Kingdom

ABSTRACT

Successful volumetric inspection of LMFBR primary circuits, and also much of the secondary circuit, is dependent on the availability of satisfactory examination procedures for austenitic welds. Application of conventional ultrasonic techniques is hampered by the anisotropic, textured structure of the weld metal and this paper describes development work on the use of longitudinal wave techniques. In addition to confirming the dominant effects of the weld structure on ultrasound propagation some results are given of studies utilising deliberately induced defects in Manual Metal Arc Welds in 50mm plate together with preliminary work on the inspection of narrow austenitic welds fabricated by automatic processes.

1. INTRODUCTION

Successful volumetric inspection of LMFBR primary circuits, and also much of the secondary circuits, is dependent on the availability of satisfactory examination procedures for welds made between plates of austenitic steels such as Type 316 and 304. In order to supplement radiography in the demonstration of the structural integrity of the reactor during construction and to meet possible requirements for in-service inspection there is a need to provide appropriate ultrasonic procedures.

Application of conventional ultrasonic techniques is hampered by the anisotropic, textured, structure of the weld metal and this paper describes development work on the use of longitudinal wave techniques which are generally regarded as preferable for the examination of thick sections. In addition to confirming the dominant effects of weld structure, and hence fabrication procedure, on ultrasound propagation some results are given of studies utilising deliberately induced defects in Manual Metal Arc (MMA) welds together with preliminary work on the inspection of narrow gap welds fabricated by automatic processes.

Since it is the principal material of interest in this context for the UK fast reactor development programme, all the work to be discussed makes use of type 316 austenitic steel specimens and work has concentrated on butt welds in 50mm thick rolled plates.

The paper closes with a brief descussion of some factors involved in the application of these results to the in-service inspection of a sodium cooled reactor.

2. BASIC THEORY AND CHOICE OF TECHNIQUE

Macrographs of three manual metal arc welds are shown in Figure 1 and reveal long columnar grains which begin at a fusion face and extend into the body of the weld. The grains follow the heat flow paths in the weld during cooling and can grow epitaxially from one weld run to another as shown. The columnar structure of such welds may be broken up by mechanical deformation, or modified by heat treatment above 1050°C, but these processes cannot usually be considered for large items of plant and thus it is not generally possible to modify the weld structure following initial fabrication.

Baikie et al(1) showed that the ultrasound propagation velocity and attenuation in a 316 MMA weld is direction dependent for longitudinal waves while Launay et al(2) reported similar results for the components of a transition weld between austenitic and ferritic material in addition to providing a concise record of the practical advantages on signal/noise ratio grounds of using longitudinal waves for ultrasonic pulse echo examination instead of shear waves. Tomlinson et al(3) had reported very similar attenuation data for Inconel 182 weld metal and alpha brass while their results on a single crystal of nimonic 80A proved that the attenuation variations are not due to a grain boundary effect. Nevertheless, these anisotropic effects are not significant in measurements made on samples of rolled plate which is made up of a relatively homogeneous distribution of equiaxed grains.

While there have been numerous studies of the compositional and metallurgical phase variations in austenitic weld metal, there is a marked lack of published data on the detailed variation of the elastic properties of the material. However, X-ray diffraction results by Baikie et al(1) and Kupperman and Reimann(4) show a strong alignment of the 100 crystallographic directions of the face centred cubic structure of the weld metal along the long axis of the columnar grains. Theory indicates that such a structure will produce anisotropy of the type observed whether or not the grains are aligned in the plane perpendicular to their axes, and also lead to the deflection of ultrasound beams because the wave fronts are no longer necessarily normal to the propagation direction. Figure 2 illustrates this beam skewing phenomena with a comparison of some theoretical and experimental data for the angle of deviation of the beam of longitudinal (Cp) waves propagating through a block of weld metal.

Qualititatively similar effects are observed for shear waves. For S_V waves the skewing effect is greater than for Cp waves, and opposite in direction for most beam angles(5), and this contributes to the well known signal to noise ratio problems but the effect appears less for S_H waves(4,5). However, the use of S_H waves is currently impracticable for most applications and the remainder of this paper will be mainly confined to the consideration of longitudinal waves in order to investigate their potential effectiveness for NDT when utilising their advantage in signal to noise ratio. An important aspect, however, is the need to appreciate factors which mean that a longitudinal wave probe cannot be regarded as if it were merely a novel variety of shear wave probe.

3. STUDIES USING ARTIFICIAL REFLECTORS

As part of the investigation of the effect of weld structure on ultrasound propagation, 1½mm diameter side drilled holes were introduced into several welds and they were examined with a series of probes using both manual and automated techniques. Table I shows the results of measurements of beam angle in a specimen of Type 316 rolled plate for the five longitudinal wave angle probes prepared using a series of perspex wedges and a 12mm diameter commercial transducer.

Reflections from the holes that could be detected in the weld specimens one and two were maximised and the range, probe position and reflection amplitude recorded. The welds were examined from either side and from both the upper and lower surfaces and it was generally found that the effective beam angle differed from that in plate material. Detailed examination of the data revealed that the longitudinal waves propagate along preferred paths at 45° to the long axis of the columnar grains.

This is illustrated in Figure 3 and may be seen to agree with qualitative expectations from Fig 2 where the variation of beam skewing for the angles reported in Table I is such as to deflect a beam towards the 45° preferred direction. In contrast, for a conventional normal compression probe examination there is a defocusing effect which results in major beam bending as is also shown in Figure 3 for weld specimen two.

The differences between the grain structures of the weld specimens one and two produce significant differences in the ultrasound propagation directions and indicate that relatively small differences in the detailed fabrication procedures are important.

Work on the third specimen emphasises this. Figure 1c shows the grain structure of a weld produced in the horizontal-vertical position with appropriate choice of preparation while the welds depicted in Figures 1a and 1b were produced down-hand. For the horizontal-vertical weld the beam from a normal compression probe is favourably inclined to the grains whereas an angled beam is not, which is in direct contrast to the situation for the down-hand samples.

Clearly, the fact that the ultrasound propagation direction is a function of the grain structure makes it very difficult to accurately locate a reflector from probe position and A scan data in the conventional manner. From the data obtained during the examination of the two down-hand welds it was observed that the range values were approximately correct for the direct distance between probe emission point and reflector in spite of the beam skewing phenomena. Using a flaw detector calibrated using rolled plate velocity data the average range error was 2-5% and it was found that holes could be located satisfactorily by a triangulation technique provided that they were detectable from both sides of the weld. This is illustrated in Figure 4.

Finally for the MMA welds, the relative amplitudes of the maximum signals reflected from the holes in the down-hand welds were measured using the calibrated gain control of a flaw detector for the angle beam examinations and the results are shown in Figure 5. For each specimen the range of amplitudes for the reflections from side drilled holes is 8-12dB but the signal to noise ratio is at least 15dB which is high for austenitic welds.

Since the beam skewing and variable apparent attenuation are apparently confined to the weld metal it is of interest to examine the results obtained from an examination of narrow gap welds. The study has therefore included welds made by a special Tungsten Inert Gas (TIG) and an electron beam welding process which yield a smaller volume of weld metal than the MMA process and which can have a very different dendrite structure as shown in Figure 6.

As anticipated the beam paths in weld metal were found to be sufficiently short for beam skewing effects to be negligible for longitudinal waves while, in contrast to Figure 5, the variations in signal amplitude shown in Figure 7 are such that a useful distance amplitude correction curve can be constructed which would facilitate automated sentencing.

Figure 8 compares the results of simple automated raster scans of the electron beam weld using 45° shear and longitudinal waves. A wide time gate was used and in the illustration the amplitude of the gated signal is superimposed on the co-ordinate corresponding to the position of the probe emission point along the weld centre line which is marked. The side drilled holes are clearly detected but also of significance is the large signal generated by the fusion face during the shear wave examination.

For shear waves, the signal from the fusion face is greater than that for a 1½mm side drilled hole in the weld metal whereas the reverse is true for longitudinal waves. This result may be explained qualitatively by two effects. First there is a 25% difference between the velocity of S_V waves in plate and in the 45 degree direction in weld metal, but only a 5% difference for longitudinal waves. Thus the acoustic impedance mismatch at the fusion boundary is larger for the shear waves than for the longitudinal waves. Secondly, longitudinal waves are only weakly reflected by right angle corners as strong shear wave components are produced by mode conversion(7). Qualitatively similar effects were observed in our corresponding measurements on the narrow gap TIG weld but the shear wave signals from the fusion face were much weaker than for the electron beam weld. This difference presumably derives from the different grain direction shown in Figure 6 and the greater roughness of the fusion face in this TIG weld specimen.

4. STUDIES USING DELIBERATELY INDUCED DEFECTS

In order to examine the application of angled longitudinal wave techniques to actual inspections a number of deliberately defective MMA welds have been prepared using down-hand techniques. These specimens will ultimately be examined destructively to confirm the effectiveness of the examination techniques under laboratory conditions.

The weld defects used in the study included lack of fusion and cracking introduced into different positions in the section of welds with single Vee, double Vee and 'U' preparations. After welding the specimens were machined flat on all surfaces to remove the excess root penetration, the cap, and all distortion produced by welding.

All the welds were tested with angled and normal 2¼MHz longitudinal wave single crystal probes using both manual and automated techniques. A 12½mm diameter probe was used for the normal scans and for the angled scans a 25mm dia probe mounted on a 21° perspex wedge to give a nominal 45° beam. During the manual scans the probe was skewed slightly to maximise the signal but for the automated scans the beam centre line was kept normal to the weld centre line.

As with the samples containing artifical reflectors the specimens were examined ultrasonically from both sides of the weld using both upper and lower surfaces, and, in addition, an orthodox radiographic examination was carried out.

Figure 9 illustrates the results for a lack of fusion defect for which the A scans were recorded in digital form during an automated examination in the geometry indicated in Fig 8a. These A scans are reproduced as a time series display in Fig 8b and the approximate location of the fusion boundaries sketched in. The echoes which originated from the region of a planned defect are clearly apparent.

The value of the exercise will be fully assessed on completion of the destructive examination but, if it is assumed that the deliberate defects are approximately of the size intended, then the work indicates that fairly small defects can be detected in the laboratory.

5. DISCUSSION

The work reported here confirms that ultrasound propagation is governed by the weld structure and hence that the fabrication procedure is very important. Indeed the effectiveness of any inspection using these techniques cannot be assessed without some knowledge of the grain structure. Therefore it is not possible to assess the effectiveness of an inspection solely with the use of data gathered during the inspection, weld fabrication data are essential.

A predictable grain structure is a pre-requisite for the use of these techniques but it is not clear that they could be used for welds produced by all available welding procedures. Thus some welding procedures produce columnar structures with little evidence of epitaxial growth from one weld run to another, as shown in Figure 10, and it is apparent that there will be no continuous preferred paths through such a weld. Further work is required to investigate the inspectability of a wider range of weld structures using longitudinal waves and, in particular, work is in progress on the effect of variations in the manual metal arc welding procedure.

The data of Figures 5 and 7 clearly indicate that signal amplitude is not a good guide to the size of any reflector while the spatial variation of the magnitude of beam skewing and consequent focusing effects rule out the use of dB drop techniques. Moreover, it is clearly virtually impossible to generate a useful DAC curve applicable to MMA welds and one of the most promising techniques to overcome this sizing problem is that under development by Silk(6) which is based on time of flight measurements of the diffracted signals from the edge of defects.

In addition to the problems referred to above and to the normal evolution required to convert laboratory techniques into field inspection procedures, application of ultrasonic inspection procedures to ISI of LMFBR involves consideration of a number of other important factors. Problems arising from the inspection temperature and choice of couplant are generally recognised, while the selection of calibration blocks has been referred to above, but it is also necessary to consider the effects of sodium ingress on the detectability of surface breaking defects. Theoretical work by Temple(8) using idealised models clearly indicates that there is a threshold of crack width in the 10-100μ range below which the ultrasonic reflectivity of a sodium filled crack may be expected to decrease significantly.

Work in this area continues as part of the overall task of ensuring, in collaboration with the welding development engineers, that techniques are available to permit adequate inspection of LMFBR welds.

From a comparison of the results of the manual and automated examinations it may be concluded that the latter are generally more satisfactory and studies are in progress at RNL on the possible application of Pattern Recognition Techniques to further increase their effectiveness.

This paper has described experimental investigations on the application of longitudinal waves using probes with a centre frequency of 2¼MHz. Further work is required to investigate the possibility of there being an optimum frequency range of the type reported by Lautzenheiser and Greer(9) when using shear waves for the examination of thinner sections of austenitic material.

6. CONCLUSIONS

The experimental investigations described in this paper demonstrate that angled longitudinal waves show great promise as a practical inspection procedure for the detection of defects in austenitic welds. Nevertheless, since the propagation of ultrasound in austenitic weld metal is determined by the columnar structure of the weld, it is apparently essential that the fabrication procedure should be such as to yield a predictable, well ordered, grain structure and details of this procedure must be available to the ultrasonic examiner.

7. ACKNOWLEDGEMENTS

The permission of the Managing Director of the UKAEA, Northern Division to publish this paper is gratefully acknowledged.

8. REFERENCES

1. BAIKIE B L, WAGG A R, WHITTLE M J and YAPP D. 'Ultrasonic Inspection of Austenitic Welds'. IAEA/IWGFR Specialists Meeting on In-service Inspection and Monitoring of LMFBR's. Bensberg. March 1976.

2. LAUNAY J P, PETEUIL M and TRUMPFF B.
'Contribution to the improvement of ultrasonic testing of bi-metallic welds'. Presented to Conference on 'Periodic Inspection of Pressurised Components'. IMechE Conference Publications 1979-4 Paper C51/79 pp225-234.

3. TOMLINSON J R, WAGG A R and WHITTLE M J.
"Ultrasonic Inspection of Austenitic Welds". Second International Conference on Non-destructive Evaluation in the Nuclear Industry. Salt Lake City, February 13-15, 1978.

4. KUPPERMANN D S and REIMANN K J.
Effect of shear wave polarisation on defect detection in stainless steel weld metal. Ultrasonics. January 1978, pp21-27.

5. SILK M G, LIDINGTON B H and HAMMOND.
A Time Domain Approach to Crack Location and Sizing in Austenitic Welds. The Brit. J. of NDT - March 1980. Vol 22. No 2. pp55-61.

6. HUDGELL R J and SEED H.
Ultrasonic longitudinal wave examination of austenitic welds. The Brit. J. of NDT - March 1980. Vol 22, No 2. pp78-85.

7. KRAUTKRAMER J and H.
Ultrasonic testing of materials. Springer-Verlag, 2nd Edition, Section 1.63.

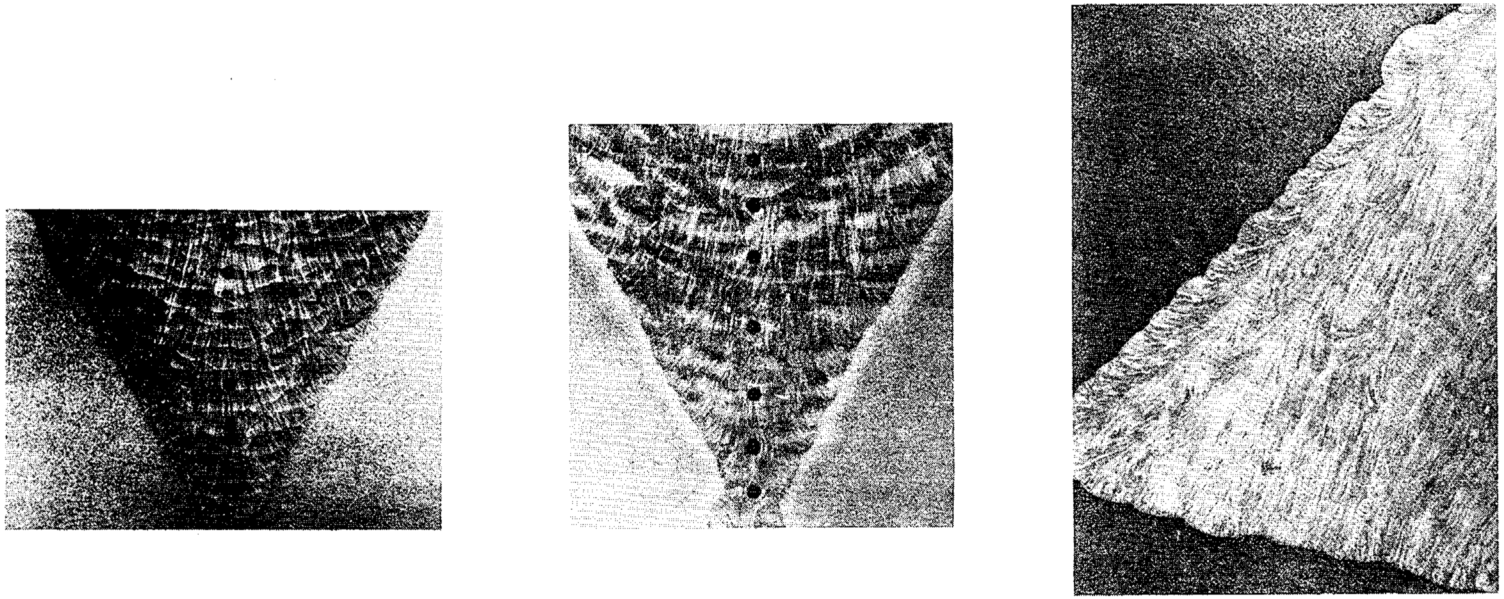
8. TEMPLE J A G.
Calculations of the reflection and transmission of ultrasound by cracks in steel filled with liquid sodium. Ultrasonics 1980 (to be published).

9. LAUTZENHEISER C E and GREER A S.
Ultrasonic inspection for stress, corrosion cracking in stainless steel. Presented to Conference on 'Periodic Inspection of Pressurised Components'. IMechE Conference Publications 1979-4. Paper C50/79. pp219-224.

TABLE I

LONGITUDINAL BEAM ANGLES IN 316 PLATE PRODUCED BY VARIOUS PERSPEX WEDGE ANGLES

Perspex Wedge Angle (Degrees)	Beam Angle in Plate (Degrees)
18	39
19.5	42
21	48
22.5	51
24	57

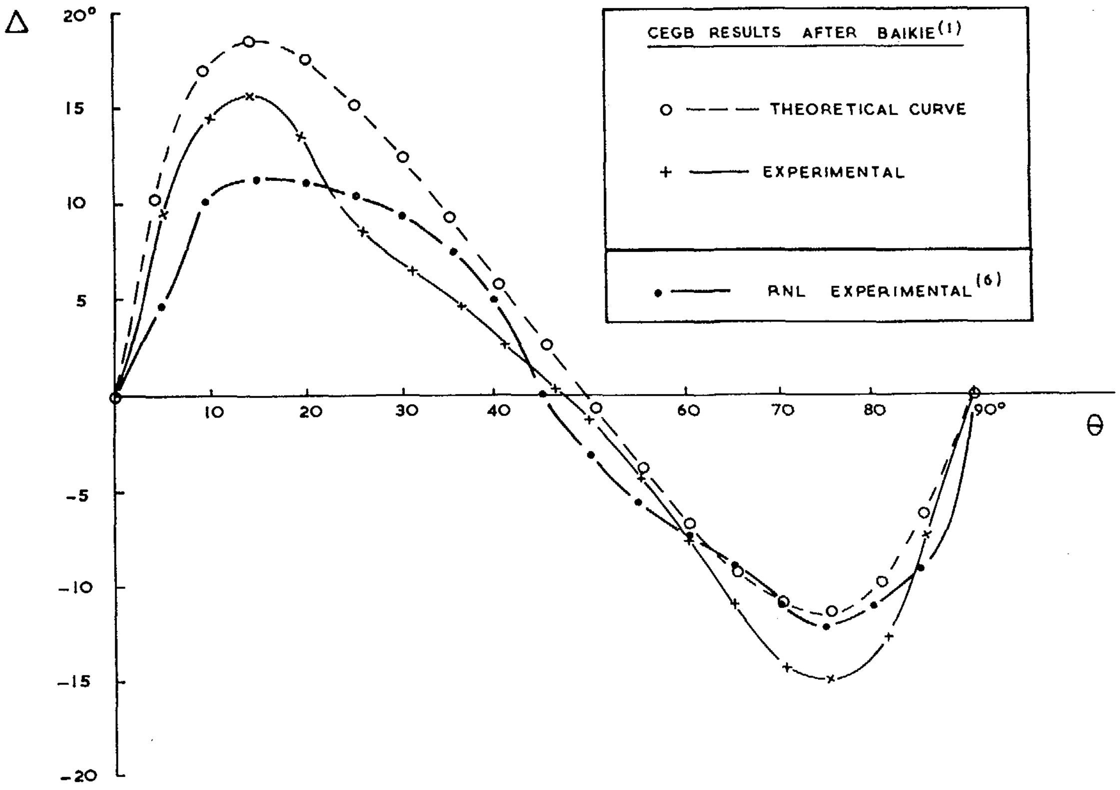


(a) Specimen 1

(b) Specimen 2

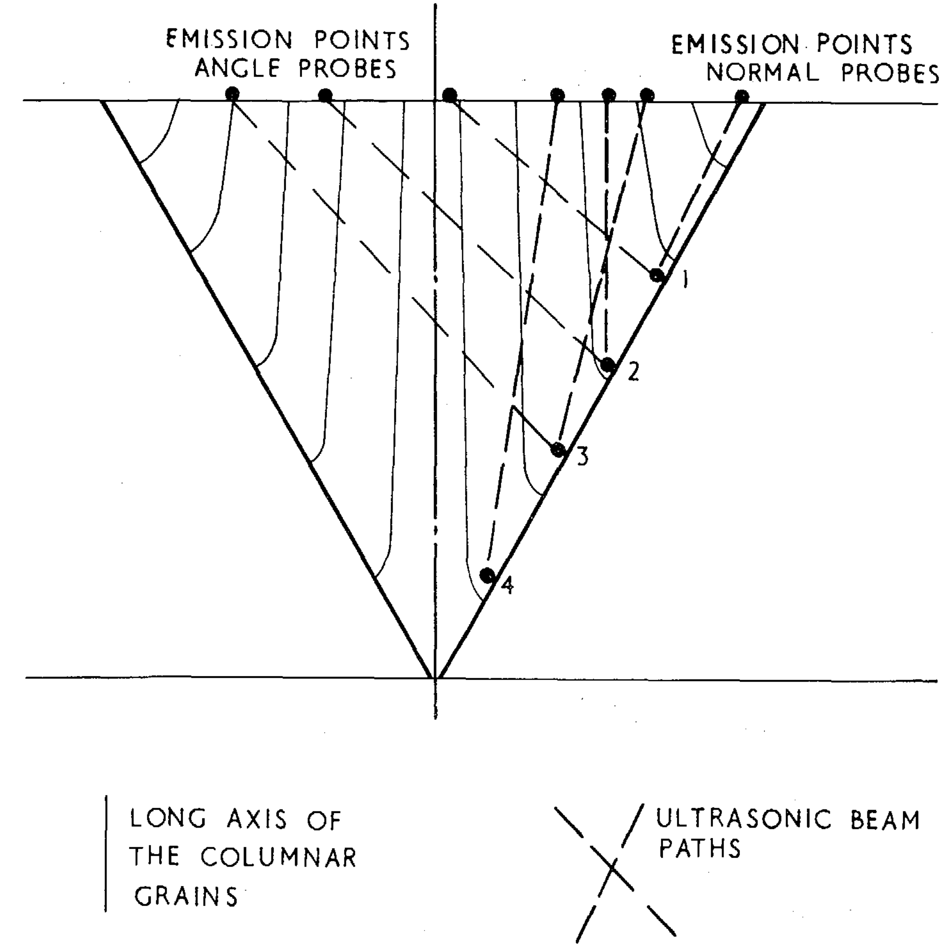
(c) Specimen 3

FIG 1 MACROGRAPHS OF THREE MANUAL METAL ARC BUTT WELDS IN 50mm THICK PLATE



SKEWING ANGLE Δ AS A FUNCTION OF THE ANGLE Θ BETWEEN THE NORMAL TO THE WAVE FRONT AND THE COLUMNAR GRAIN AXES

FIG. 2



THE DIRECTIONS OF THE MOST INTENSE PART OF BEAMS USING NORMAL ANGLED PROBES FOR SPECIMEN 2

FIG. 3

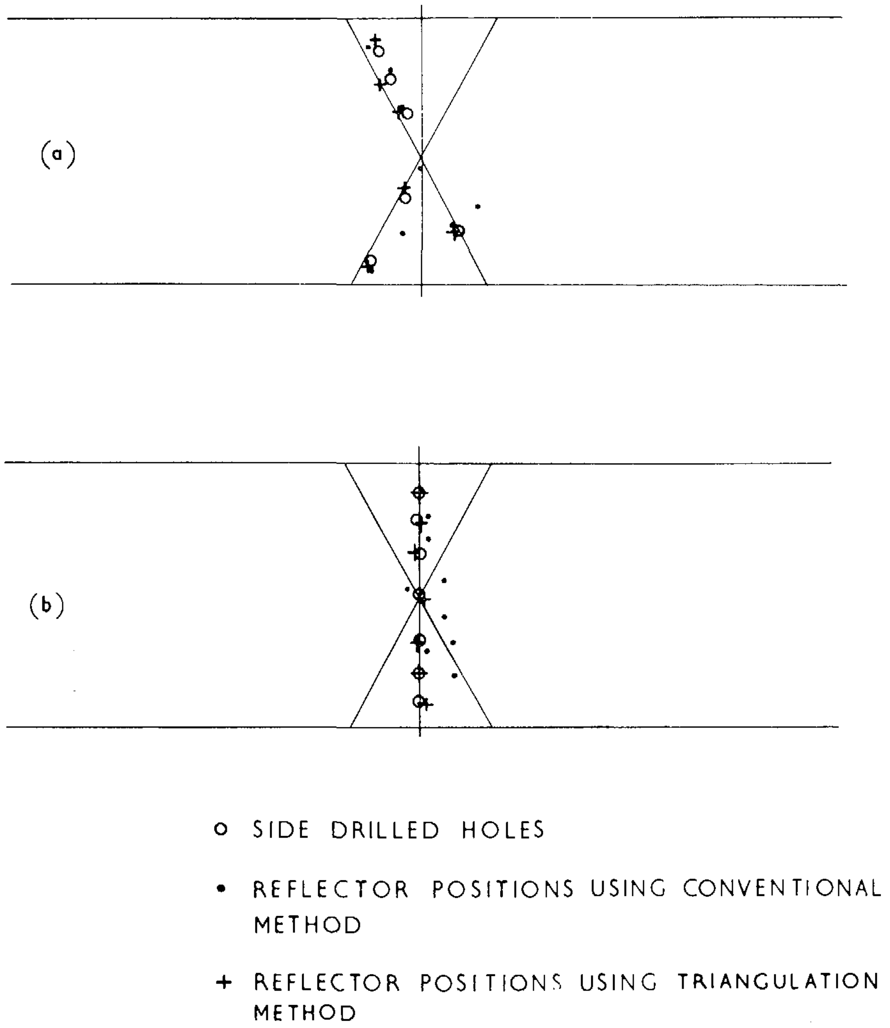


FIG. 4 A COMPARISON OF REFLECTOR LOCATION USING CONVENTIONAL AND TRIANGULATION METHOD FOR AN MMA WELD

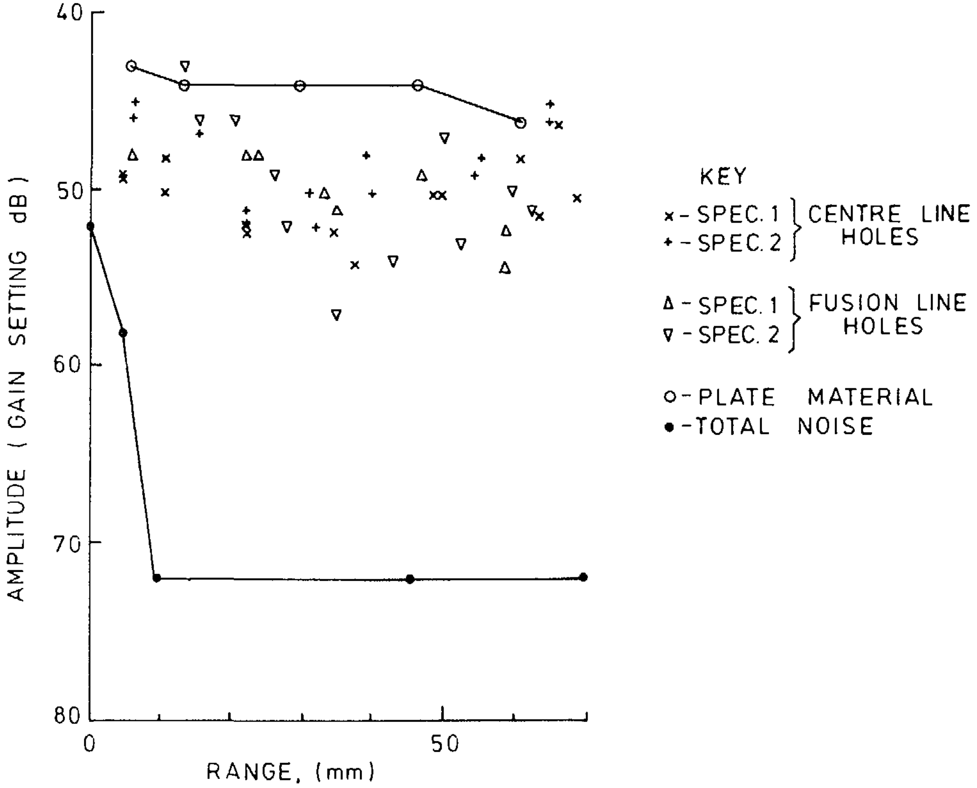
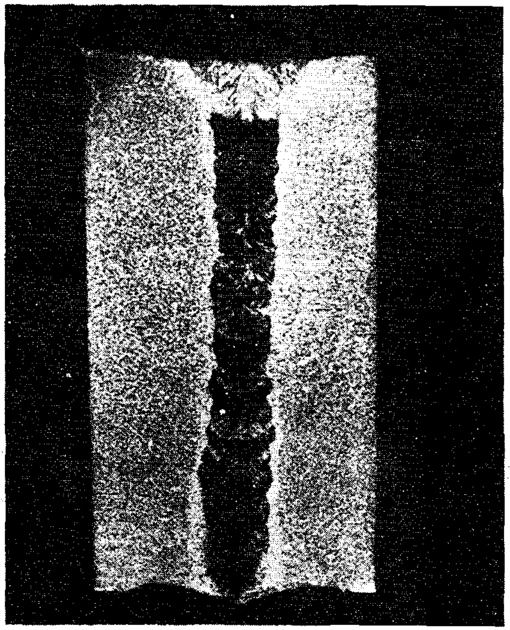
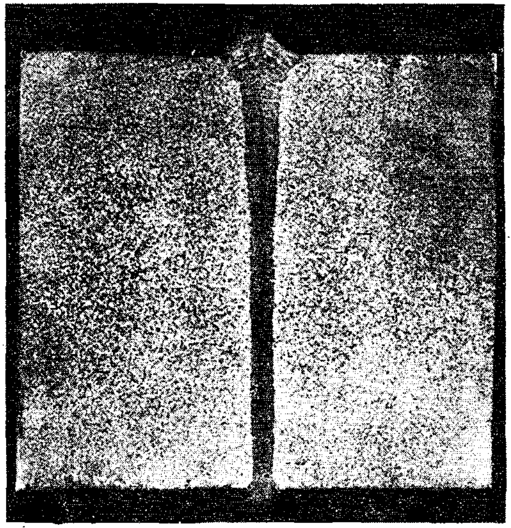


FIG. 5 AMPLITUDE RESULTS FOR DOWNHAND MMA WELDS WHEN EXAMINED FROM THE CROWN



(a) TUNGSTEN INERT GAS WELD



(b) ELECTRON BEAM WELD

FIG 6 MACROGRAPHS OF TWO NARROW GAP WELDS

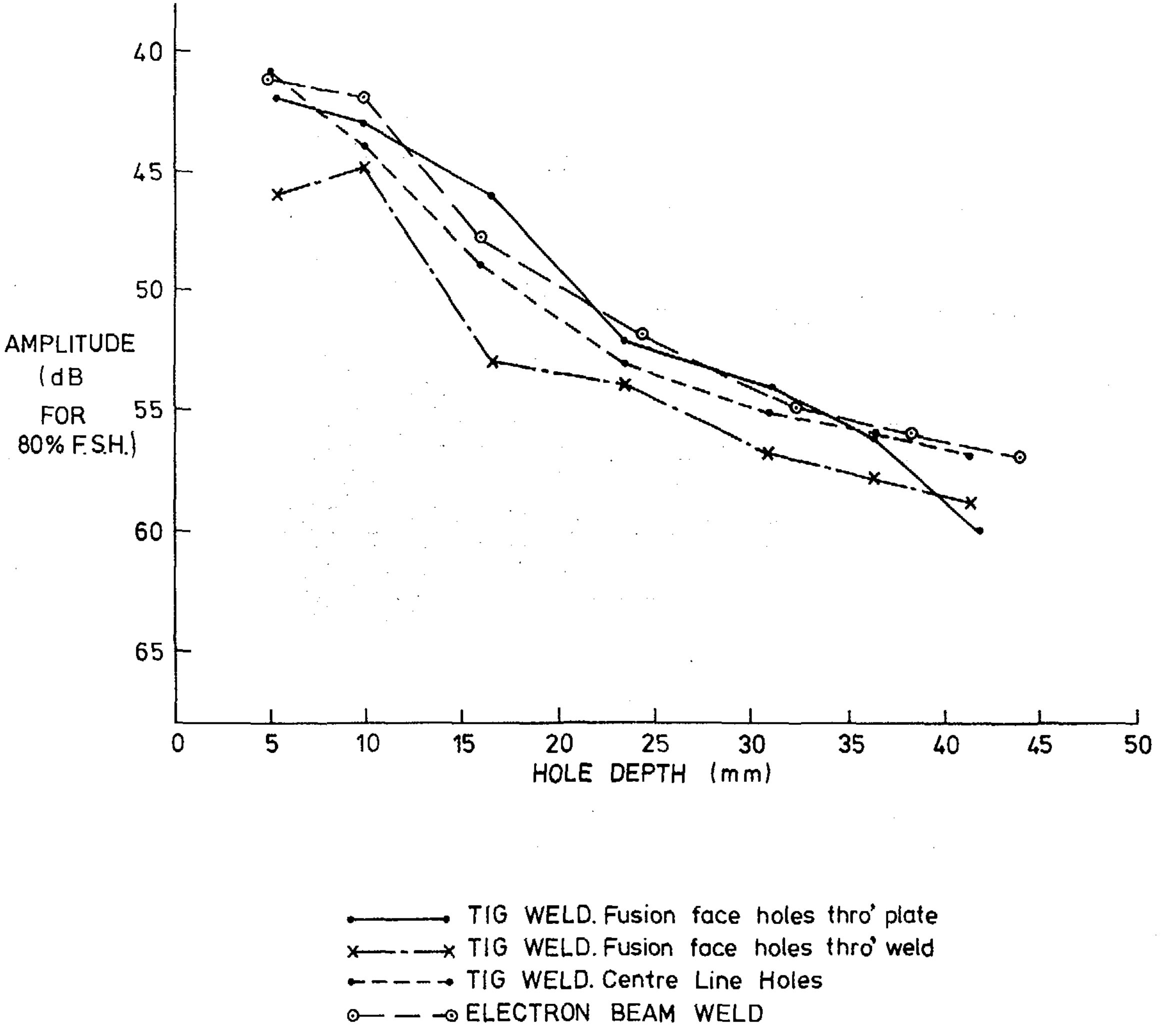
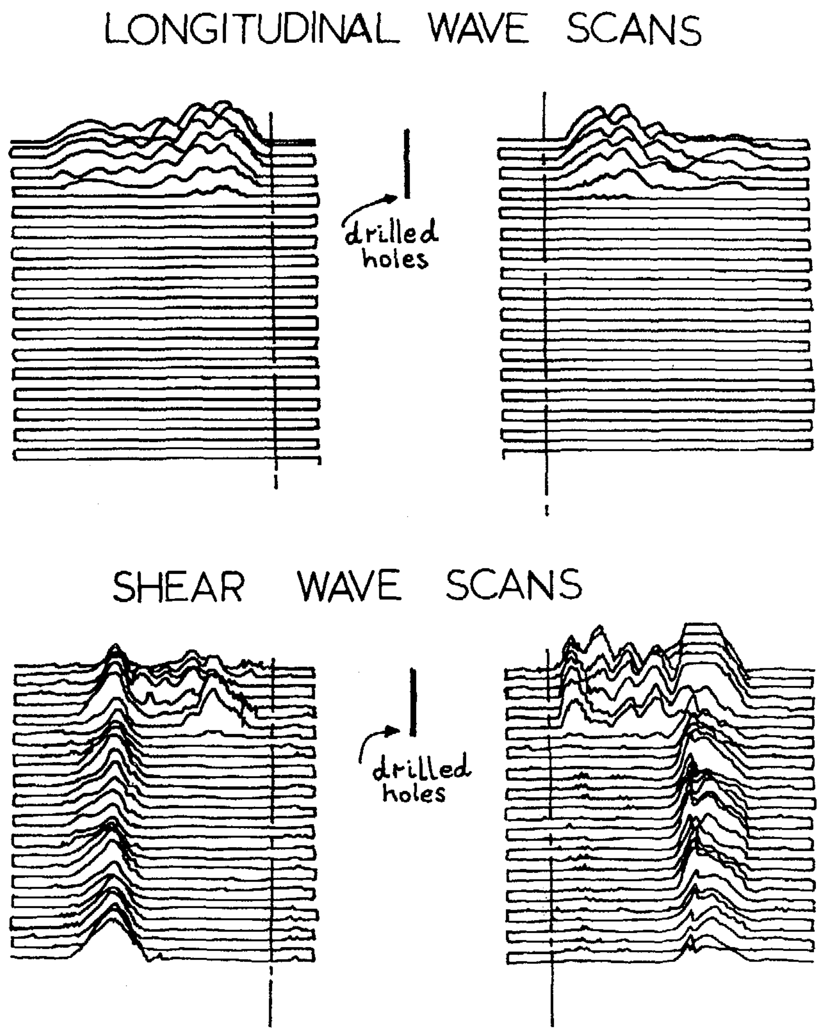


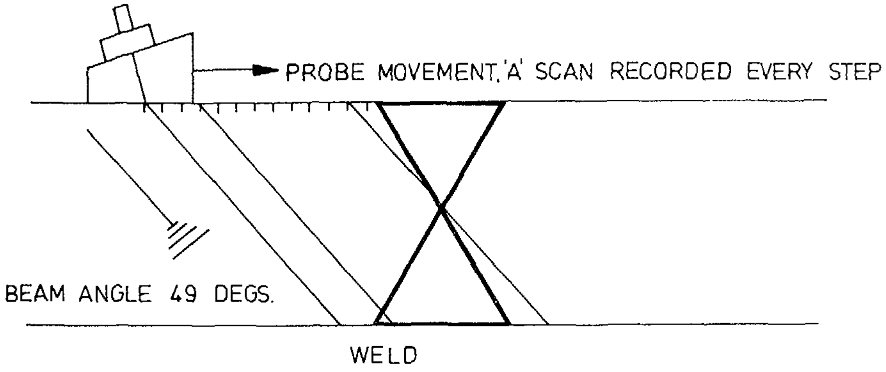
FIG. 7 AMPLITUDE RESULTS FOR TWO NARROW GAP WELDS WHEN EXAMINED FROM THE CROWN



ULTRASONIC 45° 2MH3 SCANS OF AN ELECTRON BEAM WELD

FIG. 8 RESULTS OF AUTOMATED SCANS, AN ELECTRON BEAM WELD

(a) 'A' SCAN RECORDING



(b) DISPLAY OF A SERIES OF 'A' SCANS. PROBE MOVEMENT 2mm STEPS

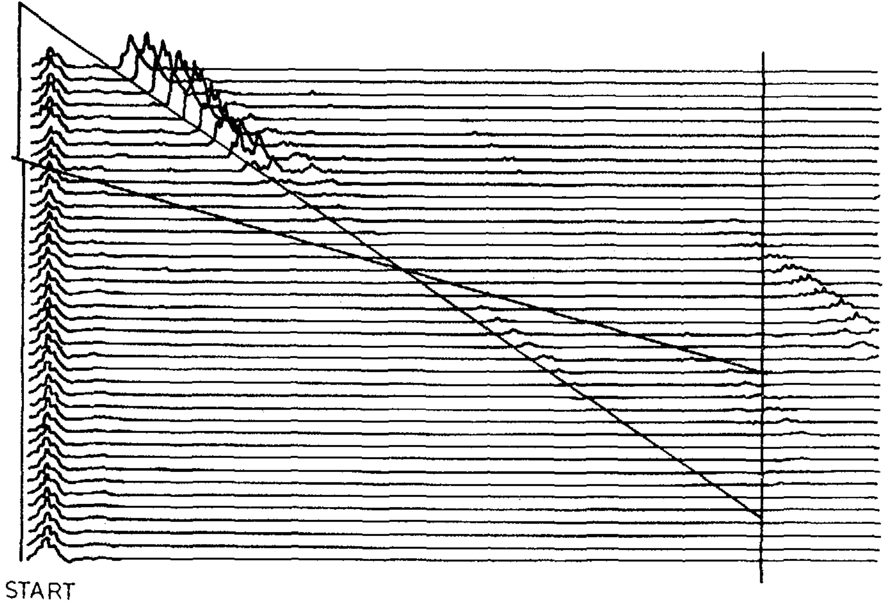
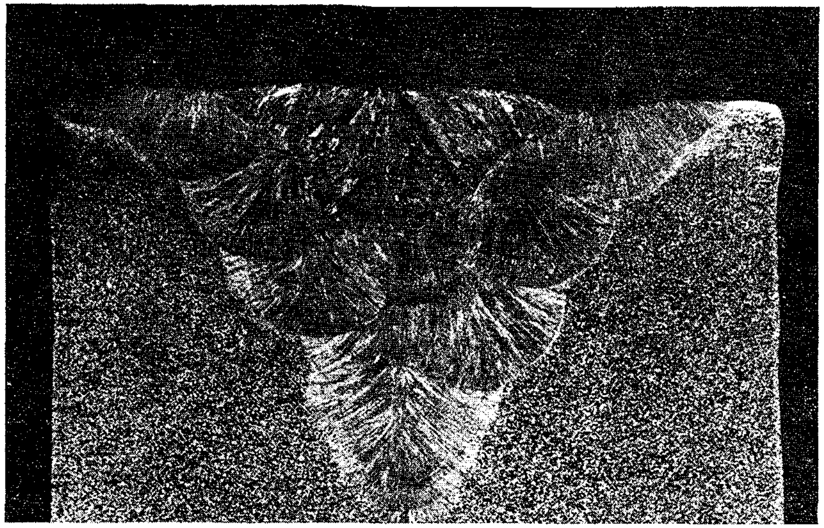


FIG 9 THE RECORDING AND DISPLAY OF A SCAN DATA FOR A DELIBERATELY DEFECTIVE WELD



MACROGRAPH OF A SUBMERGED ARC BUTT WELD IN 25mm THICK PLATE

FIG. 10

COMPARISON OF ULTRASONIC TESTING WITH SINGLE PROBES AND TRANSMITTER-RECEIVER TECHNIQUES BOTH WITH COMPRESSIVE WAVES FOR AUSTENITIC WELDS

K. EWALDS, H. BENZ
INTERATOM, Internationale Atomreaktorbau GmbH
Bergisch Gladbach
Federal Republic of Germany

Abstract

Austenitic welds with wall-thickness of 40-60 mm - typical for the SNR 300 reactor vessel - were examined in fabrication by a TR-techniques with compressive waves at 2 MHz. This technique is compared with commercially available single probes of 2 and 4 MHz. A specimen with cylindrical holes of 3 mm diameter oriented parallel to a weld was used, to measure the distance amplitude behaviour and the signal to noise ratios at different beam angles. For the worst case - sound path completly through the welding - it is shown that the TR technique is superior and a sufficient SN-ratio can be achieved. It is possible to need only two probes for 40 mm wall-thickness and an additional one for the range up to 60 mm.

1. Procect and aims

The work reported in this presentation was carried out in the frame work for developing UT inservice inspection techniques of the SNR 300 reactor vessel. It is intended to apply a TR technique (compressive waves) as proposed by BAM - with different probes matched to fixed depth ranges. In order to get