ND-R-1201(R)
CSNI Report No. 94

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OECD Nuclear Energy Agency

United Kingdom Atomic Energy Authority
Northern Division Report

The ultrasonic inspection of austenitic materials – State of the art report

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May 1985

Issued by Risley Nuclear Power Development Establishment Risley Warrington
WA3 6AT
On behalf of the
OECD Nuclear Energy Agency, 38 bd Suchet, F-75016 Paris, France

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UNITED KINGDOM ATOMIC ENERGY AUTHORITY
NORTHERN DIVISION REPORT

The ultrasonic inspection of austenitic materials – State of the art report

by

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SUMMARY

Austenitic steels are an important group of materials which are generally used for applications where resistance to corrosion, or high strength and creep resistance at elevated temperatures, are required. They are used extensively in nuclear plant.

Although ultrasonic inspection methods have been routinely used in industry for some three decades, it is well known that cast or welded austenitic components can be difficult, or even impossible, to examine ultrasonically. Development of ultrasonic techniques is therefore in progress in several countries to provide improvements which are being sought on safety and economic grounds.

This report reviews much of the available literature on the ultrasonic inspection of austenitic welds. A brief description of the relevant metallurgical characteristics is given before a consideration of the physical properties of the weld metal and the current theoretical models used to describe ultrasound propagation in it.

The largest section deals with the practical steps taken to improve the capabilities of ultrasonic inspection and includes a discussion of the problems of flaw location and sizing. The review closes with some general conclusions and suggestions for areas where further work is required.

Prepared on behalf of the Organisation for Economic Co-operation and Development, January 1985.

May 1985

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1. INTRODUCTION

Austenitic steels are an important group of materials which are generally used for applications where resistance to corrosion, or high strength and creep resistance, are required at elevated temperatures, such as in the primary pipework of a PWR or the primary circuit of a fast reactor. Austenitic steels may also be used where ductility at very low temperatures is essential, such as in cryogenic vessels, while their corrosion resistance also makes them attractive when processing foodstuffs.

Ultrasonic inspection techniques have been routinely used in industry for approximately 30 years and it has always been known that cast or welded austenitic components can be difficult, or even impossible, to examine ultrasonically. It is only in the last 8-10 years that it has been known why they are difficult to examine, and significant progress has been made towards improving inspection techniques.

Standards of safety are becoming more stringent with time and consequently there is a need to demonstrate some degree of inspection capability for the detection of planar flaws during fabrication (and also inservice) of any structure the failure of which could have serious safety or economic consequences. Thus it is clearly necessary to continue developing techniques for inspecting austenitic welds.

This Report reviews much of the work that has been reported on the ultrasonic inspection of austenitic welds. Previous reviews have been written by Caussin 1978(1) and Whitaker and Jessop 1981.(2) It was considered in late 1983 that sufficient additional developments had occurred to warrant a new review of the situation. Accordingly, the OECD Nuclear Energy Agency commissioned this state of the art survey within the programme of its Principal Working Group No. 3 (Primary Circuit Integrity) of the Committee on the Safety of Nuclear Installations. Some of the papers reviewed also mention coarse grained austenitic materials and castings. In this report we make a theoretical distinction between materials which are strongly textured and whose bulk properties are anisotropic, such as the majority of austenitic welds and castings, and materials which simply have a coarse grain structure but whose bulk properties are isotropic. Practically, however, it is less easy to make a clear distinction, since similar ultrasonic techniques are applied to both types of materials.

In this review we begin by briefly describing the metallurgical characteristics of austenitic welds which are of relevance to the problem of ultrasonic inspection. This is followed by a description of the physical properties of austenitic weld metal and the theoretical models which have been developed to explain the propagation of ultrasonic waves through weld metal. The largest section in the review deals with the practical steps that workers have taken to make inspection possible, or easier. The problems of sizing flaws in austenitic welds are also considered and, finally, we look at a few applications and draw some general conclusions.

2. METALLURGICAL CHARACTERISTICS OF AUSTENITIC WELDS

This section briefly describes the important metallurgical characteristics of austenitic welds which are relevant to ultrasonic testing.

The atoms of austenitic steels have a FCC structure at all temperatures. Therefore the macrocrystalline structure of an austenitic weld is established when it solidifies and the austenitic phase forms long columnar grains which grow along the directions of maximum heat loss during cooling. These grains can be typically one or two centimetres long (often larger in castings) and some typical examples can be seen in Fig. 1, which shows some sections through welds made by the Manual Metal Arc (MMA) welding process.

Ferritic welds do not exhibit grain structures such as that shown in Fig. 1. They undergo a solid-solid transformation from FCC to BCC during cooling, which breaks-up the columnar grains although it is sometimes possible to see the remains of such a structure in the capping run of a ferritic weld. Also when one weld run is deposited on top of another, the heat input refines the grain structure of the lower one. Metallurgically it is impossible to refine the structure of austenitic welds by heat treatment alone. The structure of austenitic welds can only be refined by heavy deformation and recrystallisation, or by applying high pressures at high temperatures as described by Lott and Malik 1983,(3) but neither of these processes is usually practical for weldments.

Thus it is only in austenitic materials which have a FCC structure that long columnar grains arise, and it is the physical properties of these grains which cause problems during the ultrasonic inspection of austenitic welds and castings.

The most common welding process used for austenitic components is arc welding which includes the following:

(i) Manual Metal Arc (MMA)
(ii) Submerged Arc (SA) or (SAW)
(iii) Metal Inert Gas (MIG)
(iv) Tungsten Inert Gas (TIG)

The columnar grains in multipass MMA welds generally grow expitaxially through successive weld beads, and the columnar structure of the weld can be controlled to advantage for ultrasonic inspection purposes, Alberry et al 1978,(4) Baikie and Yapp 1979.(5) The columnar structure of multipass SA welds looks similar to MMA welds when low heat inputs (typically 1·5 KJ/mm) are used, but for higher heat inputs (4 to 5 KJ/mm) large round weld beads are produced and epitaxial growth may not occur. It is probably unwise to generalise about the columnar structure of MIG and TIG welds.

3. THE PHYSICS OF AUSTENITIC WELD METAL

3.1 The symmetry of austenitic weld metal

The physical properties of austenitic weld metal, in as far as they influence ultrasonic inspection, were first investigated by Holmes and Beasley in 1962.(6) They observed that austenitic welds had a strong texture and that the propagation of ultrasonic waves in this material appeared to be abnormal. Using X-ray diffraction techniques they found that the long axis of the columnar grains corresponded to the 100 crystallographic direction. From this result they concluded that austenitic weld metal was anisotropic, and there was probably a connection between this and the difficulty of ultrasonically testing it. In fact the anisotropy of the elastic constants in austenitic steels had been previously reported by Saltmutter and Stangler 1960.(7) It may be noted that the elastic constants in ferritic materials are not strongly dependent on orientation within the grains.

Holmes 1963(8) investigated the effect of iron additions to austenitic welds to prevent the occurrence of cracking and also the effect of grain boundary precipitates on ultrasonic attenuation and found no effect. Thus he concluded that the high attenuation of weld metal was due to the basic properties of the columnar structure.

Renewed interest in the inspection of austenitic weld metal was reported by Peterson et al in 1975(9a) and by Baikie et al in 1976(9b) who repeated the X-ray work of Holmes and Beasley(6) and obtained the same result. Baikie also measured the apparent attenuation of compression waves in cylinders of weld metal machined from weld pads with aligned columnar grains. The cylinders were machined so that the grains were parallel with a diameter of the cylinders and it was found that the attenuation varied in a cyclic manner depending on the beam to grain angle. The attenuation was a minimum when the beam to grain angle was approximately 45° and a maximum at 0° and 90°. The velocity of compression waves was also measured in the cylinders and this was also found to be a function of beam to grain angle, with the maxima occurring at approximately 45° and unequal minima at 0° and 90°. This proved conclusively that austenitic weld metal was anisotropic. This paper was important as it established the link between the microstructure of weld metal and the ultrasonic behaviour which had eluded Holmes and Beasley.(6)

Musgrave and Miller 1954-1956(10,11,12) laid the ground work for detailed studies of the propagation of elastic waves in anisotropic media by the publication of the general theory, followed by papers describing the propagation in materials with hexagonal and cubic symmetry.

In 1978 Tomlinson et al(13) repeated the attenuation and velocity measurements reported by Baikie and established that the dependence of these on beam to columnar grain angle was due to the bulk anisotropic properties of the weld. This conclusion was supported by similar measurements on cylinders machined from alpha brass, Inconel 182 weld metal and a single crystal of Nimonic 80A. All three materials produced similar results to Type 316 weld metal, and the single crystal result proved that the dependence was not due to scattering at grain boundaries.

Tomlinson showed that the apparent variation in attenuation was due to a beam skewing phenomenon which occurs in anisotropic media and is described by Miller and Musgrave. The beam skewing which occurred in the cylindrical specimens mentioned above was measured and the results agreed satisfactorily with calculated values using Miller and Musgrave's theory. Thus an explanation was found for the strange behaviour of ultrasonic waves in austenitic weld metal.

Adler et al 1978(14) investigated the symmetry of centrifugally cast stainless steel and found that it was transversely isotropic (another description used is orthotropic). This means that the columnar grains are randomly orientated about their long axes. Thus there is a plane of isotropy at right angles to the axes of the grains. Adler also calculated compression and shear wave velocities as a function of direction in transversely isotropic material and these compared favourably with experimental values. Features of ultrasonic wave propagation in transversely isotropic media have been recently modelled theoretically by Gillan 1980.(15)

The fact that austenitic weld metal is transversely isotropic rather than cubic complicates the theory, but in terms of practicalities it makes very little difference. For example, the cubic model predicts a maximum velocity for compression waves at a beam to grain angle of 45°, whereas for the transversely isotropic model the maxima occurs at 48°. Both models predict the same phenomena, only the quantitative data varies.

Many research workers, including Kupperman and Reimann 1980(16) and Juva and Lenkkeri 1980(17) have reported the results of ultrasonic velocity measurements to investigate the symmetry of weld metal. One of the specimens used by Juva was a sphere with a diameter of 30 mm made from a large single crystal.

Curtis and Ibrahim 1981(18) used a standard X-ray diffraction technique to calibrate a surface wave technique for investigating the symmetry of austenitic welds and a casting. Surface wave velocity was found to be extremely sensitive to the direction of the wave and therefore in principle it could be used to determine quantitative texture data on unknown material.

3.2 Beam skewing

Musgrave and Miller laid the foundation for explaining the effect that material anisotropy has on the propagation of ultrasonic waves and a text-book treatment has been published by Auld 1973.(19) Musgrave's theory showed that in an anisotropic media three wave modes exist, these are a quasi-compression wave, and two quasi-shear waves with polarisations at 90°. For all modes the direction of energy flow is generally not at right angles to the wavefront, and the amount by which they deviate is commonly known as the skewing angle. The skewing angle for compression waves can be measured fairly easily, Tomlinson 1978,(13) but this is not the case for shear waves. Given the variation of velocity as a function of beam to grain angle, the skewing angle can be determined by constructing the slowness surface, which is the inverse of velocity plotted against beam to grain angle. The skewing angle is found by constructing the tangent to the slowness surface at the beam to grain angle of interest and then measuring the angle between the normal to the tangent and a line passing through the centre of the surface.

Austenitic welds and castings exhibit beam skewing in all directions apart from the plane at right angles to the long axis of the columnar grains, Fig. 2, after Silk 1980(20) shows the calculated beam skewing effect in transversely isotropic austenitic weld metal for compression waves and both shear waves.

Tomlinson(13) ascribed the cyclic variation in the apparent attenuation of compression waves in weld metal to variations in the beam width caused by the beam skewing phenomenon. For beam to grain angles between 30° and 60°, the gradient of Fig. 2 is such that fairly narrow beam widths occur resulting in relatively high sensitivities. Whereas at beam to grain angles of 0° and 90° the gradient is such that wide beam widths occur resulting in relatively low sensitivities.

Compression waves are less affected by the beam skewing phenomenon than are vertically polarised (Sv) shear waves. However, horizontally polarised (Sh) shear waves are even less affected than compression waves, but they are difficult to generate without special equipment. Choice of wave mode for the inspection of austenitic welds is described in Section 4.1.

Kupperman and Reimann 1983(21) have visualised ultrasonic compression and shear wave beams after they have passed through austenitic weld specimens and the distortions to the beam shape caused by skewing have been observed. Most of the distortions could be explained by assuming that the weld metal was transversely isotropic.

3.3 Theoretical models to explain the effect of anisotropy on ultrasonic wave propagation

Silk 1981(22) developed a computerised ray tracing model for predicting the geometrical effects of anisotropy on the propagation of an ultrasonic wave through a transverse section of an austenitic weld. The weld preparation chosen was a symmetrical V which was divided up into twenty-five regions and the orientation of the columnar grains in each could be varied to model a real weld. Ultrasound beams are traced through the weld and it is assumed that Snell's Law is obeyed at the boundaries between regions. At the boundary between plate and weld metal, an additional calculation is performed to compensate for the difference in physical properties. The model has been extensively used for predicting time of flight data for ultrasonic beams which are diffracted or scattered from flaws in austenitic welds, see Section 4.5.2 (b). The model does not provide amplitude data.

Thomson and Farley 1983(23) have developed a theoretical model for predicting beam shapes in weld metal. The model is based on diffraction theory and the active face of the transducer is considered to be an infinite number of point sources which emit spherical waves (Huygen's wavefronts). The far field beam shapes are obtained by summing the contributions that each point source makes taking into account the phase difference due to different path lengths. For transversely isotropic media, the wavefronts are generally elliptical. The model clearly demonstrates the effect of phenomena such as beam skewing, and the beam shapes predicted by the model indicate that very different probe characteristics are required for the inspection of austenitic welds compared to those for ferritic welds.

Thomson and Farley claim that when the model has been fully developed it should be possible to predict the reflectivity of flaws and hence determine the best beam angles to examine austenitic welds. Reflectivity behaviour in anisotropic materials is different to that in isotropic materials, such as ferritic welds where the angle of incidence equals the angle of reflection. In anisotropic materials the reflection behaviour is influenced by the direction of the wavefront normals rather than the direction of energy flow, and the angle of incidence does not necessarily equal the angle of reflection. Using their model, Thomson and Farley compare the reflectivity of a flaw in an austenitic weld to compression waves generated by a 45° and a 60° probe. Although most of the energy from both probes flows at 48° due to the skewing effect, the predicted direction of the reflected beam was markedly different for the two probes. Ogilvy 1984(24) has calculated the reflection behaviour for a full range of beam angles and shown that in theory an appropriate choice of transducer will permit pulse echo methods to be used for most flaw orientations. No experimental work has yet been reported on the angular reflectivity of flaws in austenitic weld metal but, in theory, beam skewing should not preclude the use of several nominal beam angles to allow for variations in defect orientation. (In this context, the nominal beam angle of a probe is the beam angle observed in isotropic (e.g. plate) material.)

3.4 Scattering

In any material the amplitude A of an ultrasonic wave decreases exponentially according to $A = A_0 \exp(-ax)$ in its passage through a material, where x is distance, A_0 is the amplitude at x_0, and a is the attenuation coefficient which has scattering and absorption components, Goebbels 1978.(25) The scattering (or absorption) of ultrasonic waves in solids is usually due to interactions with grain boundaries, inclusions, precipitates, flaws, dislocations, vacancies and magnetic domains, Green 1980,(26) Shyne 1980.(27) Some interactions will be more important than others and for austenitic materials grain boundary scattering will be very important. Scattering can lead to very low signal to noise ratios when testing austenitic components and the steps which can be taken to reduce the effect it has are discussed in Section 4.3.

3.4.1 Scattering in equiaxed polycrystalline materials

In an ideal equiaxed polycrystalline material the grains will on average be round, but to fill all the space they will have a variety of shapes, and also their diameters will vary over a wide range. The grains will generally be misaligned so that at the boundary between two grains an ultrasonic wave will be partially reflected (scattered), or it may even be mode converted due to the mismatch in the acoustic impedances.

For polycrystalline materials which do not have a texture scattering can be qualitatively explained by the following equations which Papadakis 1968(28) refers to as the Lifshits-Parkhamovskii 1950(29) and Merkulov 1956(30) theory.

$$\text{for} \quad \lambda > 2\pi D \quad a = K_1 f^4 D^3 \qquad \ldots (1)$$

$$\text{for} \quad \lambda \leqslant 2\pi D \quad a = K_2 f^2 D \qquad \ldots (2)$$

where λ = wavelength

D = average grain diameter

f = frequency

a = attenuation coefficient

K_1 and K_2 are scattering coefficients which depend on the elastic constants of the material

The scattering described by Equation (1) is called volume (D^3), or Rayleigh scattering after Lord Rayleigh 1894(31) who first investigated the subject, and that described by Equation (2) is called stochastic or diffusive scattering. Papadakis 1965(32) has published Tables giving the scattering coefficients for a large number of elements and the variation is substantial.

For materials in which $D < 0 \cdot 1$ mm the predominant attenuation process for ultrasonic waves is Rayleigh scattering, since the approximate frequencies at which $\lambda = 2\pi D$ for compression and shear waves is 10 MHz and 5 MHz respectively. For coarse grained materials, $D > 0 \cdot 5$ mm, the predominant process is stochastic scattering.

In the situation where $\lambda \ll D$ the grain boundaries are treated like mirrors. This has been investigated by Mason and McSkimin 1948(33) who found that scattering was independent of frequency and inversely proportional to grain size, i.e. $a = K_3 D^{-1}$.

Goebbels and Holler 1978(34) have reported a method for measuring the grain size of steel by ultrasonic back scatter measurements using a single frequency transducer. Their explanation of scattering is extremely clear.

3.4.2 Scattering in materials with preferred orientation or texture

The effect of preferred orientation is usually to reduce scatter. Papadakis 1965(35) has proposed a semi-quantitative two-dimensional model for slightly anisotropic grains of hexagonal symmetry, but the general theory for this case and also textured materials which are usually strongly anisotropic has not been developed yet. Where there is a tendency for high modulus directions to align with low modulus directions, then scattering will be high. Conversely, if the high and low modulus directions are separately well aligned, scattering will be low. In the ideal case where alignment is perfect no scattering will occur.

The columnar grains in austenitic welds can be up to 20 mm long, whereas their diameters are typically 0·5 mm. Morse 1948(36) investigated scattering from cylinders and found that the scattering power for a single cylinder depended on A^2f^3, where A is the cross-sectional area and f the frequency.

Papadakis(28) also points out that where $2\pi D < \lambda < 2\pi L$, where D is the average small dimension and L is the average long dimension of the grains, that scattering must obey different laws for different directions. For compression wave beams in austenitic MMA welds, it is very easy to demonstrate experimentally that scattering is higher when the waves are directed across the grains than when they are directed along the grains. The reason for this is that the grains are well aligned along their length, therefore, the boundary conditions from grain to grain are well matched in that direction and scattering is relatively low. Whereas, in the direction at right angles to their length, the grains are randomly orientated, hence large mismatches occur resulting in relatively high scattering. This is generally the case for materials with preferred orientation. For shear waves propagating at right angles to the long axes of the columnar grains, scattering is greatest when the direction of polarisation is at right angles to the long axis of the grains.

The theoretical model developed by Silk(22) (Section 3.3) predicts that the degree of scattering should be dependent on the beam to grain angle. Ermolov and Pilin 1976(37) claim to have calculated the noise due to grain boundary scattering in anisotropic materials for the near and far fields of plane ultrasonic transducers and also for the focal point of a focused transducer.

4. TESTING WELDS

This section describes some of the measures taken to improve the ultrasonic inspection of austenitic welds.

4.1 Wave mode

Shear waves are the natural choice of wave mode for ultrasonically inspecting weldments, since for beam angles in the range 40° to 60° no energy is lost by mode conversion upon reflection at the half skip distance. Unfortunately the propagation of Sv shear waves in austenitic weld metal is very complicated. Several authors have reported that the velocity can vary by a factor of 25% depending on direction, e.g. Kupperman and Reimann 1978.(38) Figure 2 shows that Sv waves may be skewed by as much as 30°, which is approximately twice as much as for compression waves. Thus the focusing/defocusing effects for Sv waves will be much greater than for compression waves which makes them more difficult to use.

Shear waves are more strongly scattered in austenitic welds than are compression waves and, furthermore, scattered compression waves are often mode converted into shear waves, Papadakis.(28) Thus the signal to noise ratio of shear wave examinations are usually lower than those of compression wave examinations at the same frequency, and this is not simply due to the smaller wavelength of the former.

Juva and Lieto 1980(39) reported that they preferred shear waves for the inspection of MMA welds with thicknesses in the range 2 mm to 10 mm, while Edelmann 1981(40) recommends that special techniques should only be considered if conventional methods have been shown to be unsuccessful. Ibrahim et al 1982(41) and Kapranos et al 1982(42) state that shear waves can be effective for the detection of fatigue cracks in the HAZ of austenitic welds and they also comment on the effect of stress and beam angle on crack detection. Kapranos 1984(43) comments further on the effect of stress on the detection of cracks and concludes that it may be used to differentiate between real and false indications.

Fusion face, or root flaws, may be detected in thick austenitic welds using shear waves, providing this does not involve long path lengths in weld metal. However for the volumetric examination of thick welds, several workers Trumpff et al 1980,(44) Sandberg 1980,(45) Hudgell and Seed 1980(46,47) and Gray et al 1980(48) have concluded that compression waves are to be preferred to shear waves. Hudgell and Seed have demonstrated that even for compression waves the structure of the weld has a dominant effect on ultrasonic propagation. Beam angles in weld metal are difficult to estimate, since they skew towards the low attenuation paths at 48° to the grains, Hudgell and Seed 1980.(46,47) Providing it is possible to exploit the low attenuation directions, reasonable sensitivities can be achieved in 50 mm thick MMA welds. However, it was found impossible to construct a meaningful distance amplitude correction (DAC) curve since small variations in the columnar structure of the weld produced large variations in the width of the ultrasonic beams. In situations where it was impossible to exploit the low attenuation directions, the sensitivity of the ultrasonic examinations was poor.

Angled compression waves can only be used to volumetrically examine a weld up to the first half skip distance, since most of the energy of the incident beam is lost to a mode converted shear wave upon reflection. For the same reason, compression waves are not as sensitive as shear waves for the detection of surface breaking flaws. Edelmann(40) has investigated the amplitude of reflected shear and compression waves from slots of various depths and found that for the former the reflected signal rises monotonically until it saturates for a slot depth of approximately 4 mm at 2·25 MHz. For compression waves, the amplitude of the reflected signal oscillates and it is always much smaller than the reflected shear wave.

A disadvantage of angled compression wave probes is that they also generate a shear wave beam component and the detection of flaws or geometric reflectors by this component can lead to confusion T/R probes (see Section 4.2) are less affected by this problem than are single crystal compression wave probes.

To examine an austenitic weld volumetrically using compression waves, it is necessary to machine the surface of the weld so that the probe can be scanned across it. This is a consequence of being restricted to the first half skip distance when using compression wave probes.

Horizontally polarised Sh shear waves are skewed less than compression waves, see Fig. 2, but they cannot be generated when using liquid couplants, therefore they are not a competitive wave mode for routine inspection applications. However, with the development of electromagnetic acoustic transducers (EMATs), they are of theoretical interest. Kupperman and Reimann(38) were the first workers to realise the potential of Sh waves for the inspection of austenitic weld metal. Their simple tests indicated that Sh waves are probably superior to compression waves for penetration and sensitivity to flaws in weld metal, furthermore they are less easily mode converted than Sv waves. Therefore, Sh waves are potentially very attractive and the results of a more recent comparison of the signal to noise ratios for the various modes are given by Goebbels and Kapitza 1984.(49)

4.2 Transducers

There are two simple measures that can be taken to reduce the degree of scattering that occurs during ultrasonic testing

(i) Use highly directional or focused transducers.

(ii) Use highly damped transducers.

Both measures reduce scatter by ensuring that the volume of weld metal insonified at any one instant in time is kept to a minimum. Kraus and Goebbels 1978(50) state that the mean back scattering amplitude of the pulse echo technique as a function of sound path length is proportional to the square root of the pulse length. Ermolov(37) states that focusing produces the best results. Heinrich et al 1982(51) comes to a similar conclusion by recommending that it is important to make sure that the ratio of the sound field diameter to the reflector diameter is as small as possible.

Ermolov adds a third step which is frequency selection to obtain the maximum signal-to-noise ratio. Several authors have commented that austenitic weld metal behaves like a low pass filter, e.g. Neumann et al 1980,(52) and this leads to the obvious deduction to use low test frequencies.

Opperman and Crostack 1980(53) electrically drove ultrasonic probes with bursts of continuous waves to investigate the amplitude of signals scattered by grain boundaries and reflected by flaws as a function of frequency, and they concluded:

(i) For a given testing range in the material there was an optimum test frequency which yielded the highest signal-to-noise ratio.

(ii) The spectral composition of an ultrasonic pulse was more important than the pulse length.

Neumann et al(52) comment on the effect of probe bandwidth on signal-to-noise ratio. They suggest that there is some advantage in seeking a compromise between broad and narrow band probes, since the high frequency components of the former will be contributing to the scatter, while the signal bearing flaw information may not contain any high frequency components. Whereas at the other extreme, narrow band probes tend to generate false indications by interference at grain boundaries. On the whole, probes with a short pulse length are generally favoured for the examination of coarse grained material.

The most important development in probe technology for highly attenuative materials was the development of twin crystal probes with overlapping beams. These are known as SE or TR probes, and have been developed mainly at Bundesanstalt Fur Material Prufung (BAM) Berlin and by Roentgen Technische Dienst bv (RTD), Rotterdam. Neumann et al 1976(54) report theoretical work based on the Kirchoff diffraction theory for the design of TR probes, and experimental measurements of beam profiles are also reported. Neumann et al 1979(55) also described the development and performance of TR probes.

TR probes are designed so that the transmitter and receiver lobes of the desired wave mode overlap at a certain depth and, consequently, the sensitivity is a maximum at this depth. The individual transmitter and receiver elements can be either side-by-side or one in front of the other. The average TR probe may be used to examine a 15 mm, or possibly a 20 mm thick depth zone, such that three probes would be required to examine a 50 mm thick weld. The published design information does not appear to allow for beam skewing effects, but the occurrence of transverse isotropy in some weld metal will reduce the perturbing effect of beam skewing when the probe elements are side-by-side.

Ganglbauer et al 1979(56) and Frielinghaus et al 1979(57) have commented that for TR probes:

(i) The examination time is protracted since several probes are required for thick sections.

(ii) Each depth zone of a weld is only examined with one beam angle.

(iii) The correlation between signal amplitude and the size of reflectors is unsatisfactory.

Special probe designs are required to examine components with curved surfaces, and problems have been encountered with the detection of transverse flaws. However TR probes are probably indispensible for the examination of extremely difficult materials such as stainless steel castings, see Jurenka 1983(58) and Rose et al 1978,(59) but for the less difficult materials, single crystal probes are much easier to use. Thomson and Farley(23) have discussed the significance of detailed differences in the designs of commercially available probes.

Edelmann and Hornung 1982(60) have successfully tested a creeping wave probe for the detection of surface breaking flaws in transition welds as a substitute for dye penetrants. Creeping waves, which are also known as head waves, are 90° compression waves, and the development and characteristics of probes to produce this wave mode are described by Ermolov et al 1978.(61) A creeping wave is used as the reference for timing diffracted or scattered compression waves in the diffraction technique after Silk,(20) see Section 4.5.2 (b). Failure to detect the creeping wave may indicate the presence of a flaw near the surface. On clad ferritic material, the observed creeping wave travels just below the cladding as the attenuation/scatter is lower than in the cladding.

Multimode probes have recently been applied to the inspection of austenitic welds for the detection of surface breaking flaws at the half skip distance. The principle of the multimode probe is that a shallow angle shear wave is generated in the base metal adjacent to an austenitic weld and this mode converts to a large angle compression wave at the half skip distance, and it is this wave which is used to detect cracks in the austenitic weld. Gruber et al 1984(62) have reported the application of multimode probes for the detection of intergranular stress corrosion cracking in PWR primary circuit piping, and for other applications where compression and shear wave components interact to provide improved defect detection compared to single mode probes.

Elsley and Fortunko 1981,(63) Fortunko and Moulder 1982(64) point out that Sh waves can be transmitted through weld metal parent plate interfaces without significant reflectors or mode conversions occurring, and therefore the number of unwanted ultrasonic indications is kept to a minimum. They report the performance of a low frequency (440 KHz) pitch catch and transmission EMAT system which has a pulse length of 40 microseconds. This has been used to detect lack of penetration and cracks in the girth welds of 12 · 7 mm thick Type 304 stainless steel pipe. The resolution of the system was obviously poor, but the signal-to-noise ratio appeared to be adequate for the detection of large flaws. As referred to earlier, Goebbels and Kapitza(49) refer to further data on this topic.

4.3 Signal processing

Grain boundary scattering can produce large spurious signals and these can severely reduce the signal-to-noise of ultrasonic examinations. During an ultrasonic examination scattering is observed as the summation of all the reflections from grain boundaries in the ultrasonic beam which arrive at the receiver at any one instant in time. Constructive and destructive interference will occur between flaw and scatter signals, and without taking special steps it is impossible to tell one from the other, since they are coherent. To improve the signal-to-noise ratio it is essential to render them incoherent.

4.3.1 Signal averaging

Kraus and Goebbels(50) suggested that flaw and noise signals could be rendered incoherent by:

(i) Spatial signal averaging.
(ii) Frequency signal averaging.
(iii) Directional signal averaging.

In all three cases small changes in probe position, frequency and angle of incidence lead to stronger changes in the grain noise than the reflections from flaws, to a first approximation. Substantial improvements in signal-to-noise ratio can be achieved at the expense of the additional time required to carry out an examination, and also the additional equipment required to average A scans and move the ultrasonic probes, etc.

Ermolov and Pilin(37) describe spatial averaging very precisely. 'The amplitude of flaw echo signals is determined by the direction of the probe and the flaw itself, it will vary according to the motion of the probe and, in the process of accumulation (averaging), it will manifest itself as a regular (highly correlated) signal. Structural noise signals exhibit arbitrary, random values (insignificantly correlated) during the movement of the probe. Therefore, in accordance with the probability theory where there is a flaw signal, the accumulated signal is greater than that arising where only structural noise is present.'

Murali et al 1981(65) describe a practical application where spatial averaging was used to reduce the grain noise from ultrasonic examinations of butt welds in Type 304 stainless steel pipes. A box car integrator was used to perform the averaging.

Newhouse et al 1980(66) reported that instead of shifting the centre frequency of the transmitted pulse of a broad band probe, as described by Kraus and Goebbels,(50) it is possible to apply split spectrum processing to achieve the same objective. The spectrum of the received signal was split into bands and then inverse Fourier transformed and normalised. An algorithm was then applied which performed an averaging function and this resulted in a large improvement in the signal-to-noise ratio.

Day 1979(67) reports a directional signal averaging technique applied to a transition weld between Alloy 800 and Type 316 stainless steel, by combining the results of weld scans carried out with different beam angles. An improvement of 8 dB was achieved in the signal-to-noise ratio for the detection of spark eroded notches using 0·5 MHz and 1 MHz immersion probes to generate shear waves in the 25 mm thick welds. Day calculated that the probability of a noise signal exceeding the amplitude of the signal detected from a 10% notch was typically 10^{-3} per scan of the weld, therefore false calls were expected.

Kraus and Goebbels(50) have investigated the instrumentation problems involved in averaging large numbers of A scans. For example, they have compared the advantages and disadvantages of averaging rectified and unrectified A scans and that of digital and analogue equipment.

4.3.2 Pattern recognition

Pattern recognition is an important part of the science of signal processing. The objective is to take as many clues as possible from a data set and find out which of them relates to the quantity required. One pattern recognition procedure that has been widely discussed in the present context is Adaptive Learning Networks (ALN) which is a trade name of Adaptronics Inc.

The process of applying ALN to an NDT problem follows a fairly standard course. As many representative specimens as possible are procured and these are divided into two sets. One set is used to 'train' the system, while the other is used to check it. Large amounts of data are then gathered from the training specimens and signal processing functions are applied to the data in order to establish whether any one, or combination of these functions will provide a confident means of achieving an objective. For example, an objective might be to identify the ultrasonic signals which originate from intergranular stress corrosion cracks (IGSCC) near butt welds in stainless steel pipes, as opposed to those that originate from geometrical features associated with the welds, see Mucciardi 1980.(68) This process is called feature selection.

The final stage is to generate classifiers or networks. All the features which have proved useful are fed into the classifiers where they are combined to produce a decision. The specimens set aside for testing are used during this stage to prove the performance of the system on data which it has not processed previously. Some examples of the application of ALN or pattern recognition are given below.

Rose et al 1980(69) applied ALN to the detection of IGSCC in thick wall stainless steel pipes. A high success rate was claimed even though the figures showing the performance of the selected features indicate that they were rather poor for decision making purposes.

Jusino et al 1983(70) experimented with ALN by applying it to the ultrasonic waveforms detected from fatigue cracks in 57 mm thick butt welds in centrifugally cast stainless steel pipe. The objective of the exercise was to characterise the waveforms for thirty-five signal processing features (or parameters) which appear to have been chosen at random. No general conclusions are reported on the merits of ALN for sorting crack signals from spurious indications, although some vague probability data is reported for the detection of cracks.

As part of the work in support of the American fast breeder reactor programme Mech 1983,(71) describes the signal processing methods tested for the examination of 10 mm thick pipework. Electro discharge machined notches with depths of 6% to 55% of the wall thickness were studied and an ALN was found to give better results than the alternative discrimination methods tested.

Shankar et al 1978(72) and Mucciardi(68) claimed that an unambiguous discrimination between IGSCC and geometrical reflectors had been achieved in sample welded sections of Type 304 stainless steel piping using non-linear signal processing techniques via the ALN methodology. However, even in 1984, an NRC sponsored *round robin* reported major problems in the detection of tight cracks in cast austenitic materials, Taylor 1984.(73) Mechanical fatigue cracks could be fairly readily detected using current field ultrasonic NDT techniques which did not include signal processing, but thermal cracks could not.

Formal pattern recognition methods have become popular with the development of powerful digital computers with large storage capacities. Unfortunately in NDT applications, there has been a tendency to apply signal processing to data obtained from complex tests without due regard as to whether it is appropriate or not. In particular it must be recognised that frequency dependent attenuation in materials must lead to variations in the spectral content of a pulse as a function of range. The possible significance of these must be considered when testing for the ratio of energy at various frequencies if a varying range is involved, and a major problem with all semi-empirical methods in any application is the assessment of the confidence which can be placed in the results. From the papers reviewed above, one must conclude that some early claims for reliabilities in this field were over optimistic.

4.4 Welding parameters and inspectability

The design of a welded joint, the welding process and the welding procedure all have an effect on the ultrasonic inspectability of austenitic welds. All too often austenitic welds have to be examined on plant that was fabricated a decade ago with welds which were not designed to be inspected. Edelmann(40.60) discusses the problem of tackling 'unknown' welds under less than ideal conditions and he stresses the importance of fabricating a reference block containing a weld which is as near as possible identical to that to be examined. This requires a detailed welding procedure in order to achieve the correct grain alignment. Using the reference block, artificial reflectors are introduced and an examination procedure is developed by trying conventional techniques to begin with and progressing to special ones should they prove inadequate.

As yet very little progress has been made to specify the factors which influence the inspectability of austenitic welds, but Section 4.4.1 describes how the Central Electricity Generating Board tackled the problem for one particular weld which had to be ultrasonically tested to satisfy regulatory requirements and Section 4.4.2 discusses the effect of the welding process.

4.4.1 Weld design

Tomlinson et al 1978,(13) 1980(74) describe how the design and the welding procedure of an austenitic fillet weld between two concentric tubes in an AGR superheater were changed to make the weld much easier to examine ultrasonically. The weld was made by the MMA welding technique and the objective of the changes was to produce a columnar structure with the long axis of the grains at 45° to the axis of the tubes. The weld was built up so that its cross-section was rectangular (rather than triangular as is usually the case for fillet welds) so that it could be examined with a 0° longitudinal wave probe from two faces, and the low attenuation paths at 48° to the columnar grains could be exploited. The specification for inspecting this weld is described by Wagg and Whittle 1978.(75)

This lateral approach to the problem of inspecting austenitic welds can be applied to any joint at the design stage, but the benefits which can be derived depend on the extent to which useful changes can be made and the additional costs incurred. Also, the effect of changes to established welding procedure on mechanical properties and compatibility must also be carefully assessed.

4.4.2 The welding process

The welding process, in as far as it influences the columnar structure of a weld, see Section 2, will also influence its ultrasonic inspectability. Early studies of the interaction were reported by Peterson et al(9a) and then by Macecek 1978(76) who claimed there was evidence pointing to a solid state transformation in 18-8 weld metal such as AISI 304/308 while this subject has been discussed in detail by Thomson and Farley.(23) Most of the important points raised are summarised below.

(a) **MMA welds**

The physical properties of MMA welds have been investigated fairly extensively by many authors including Baikie et al,(9) Tomlinson et al,(13) Kupperman and Reimann 1980,(77) and Juva and Lenkkeri.(17) Therefore the characteristics of this material are well known.

MMA welds are characterised by a high degree of grain alignment which gives rise to tolerable attenuation levels for longitudinal wave beams if they can skew towards the low attenuation directions. The most difficult MMA weld to examine, using angled longitudinal waves, is the horizontal vertical weld due to the angle of its grains, see Fig. 1.

(b) **MIG welds**

Wagg 1980(78) examined a 50 mm thick MIG transition weld and found the attenuation was too high at 0·55 dB/mm to reliably detect 3 mm diameter side drilled hole (SDH) in the lower third of the weld. Beam skewing was observed which made the location of flaws difficult.

Tomlinson et al(13) commented that the grain structure of such a weld was quite different to that for a MMA weld and this was attributed to the high heat input and the deep penetration of the arc.

Much more information is required on MIG welds since it is a welding process which is becoming more popular.

(c) **SA welds**

The columnar structure of SA welds can vary considerably depending on the heat input used and very little is known about their ultrasonic properties. Therefore weld metal produced by this process also requires investigation.

(d) **TIG welds**

Wagg 1980(78) reports favourably on the ultrasonic inspectability tests he carried out on two 50 mm thick transition welds. In the middle of the weld the attenuation was 0·09 dB/mm in one weld and 0·2 dB/mm in the other, and they were judged to be more inspectable than MIG welds.

The TIG welding process may be used for narrow gap welding and Hudgell and Seed(47) have investigated the inspectability of a narrow gap TIG weld and also an electron beam weld in 50 mm thick Type 316 plate. They concluded that narrow gap welds were much easier to examine ultrasonically than welds made by the common fusion processes simply because the volume of weld metal in the former was a mere fraction of that in the latter. 2 MHz shear waves would reliably penetrate the welds but the signal-to-noise ratio was lower than that for compression wave inspections. The effects of beam skewing were not observed since the path lengths in weld metal were too short.

Thomson and Farley(23) also concluded that narrow gap welds were attractive for austenitic components and that plant designers should be aware of all the factors which influence inspectability.

4.5 Flaw location and evaluation

4.5.1 Flaw location

Flaw location in austenitic weld metal is complicated by the anisotropy of the material. Singh 1983(79) reported errors as large as 12 mm in the location of flaws using shear waves in 33 mm thick extruded stainless steel pipe. The beam angle changed from 45° at the o.d. surface to 19° at the i.d. Singh recommends that shear wave probes should be used for flaw detection, while compression wave probes should be used for flaw location since they are less affected by anisotropy.

Padaki et al 1984(80) reported very large errors using longitudinal waves for the location of artificial reflectors in austenitic welds. They concluded that the errors were due to skewing and the only way to avoid this problem was to design welds so that they were as narrow as possible (previous section).

Yoneyama et al 1979(81) carried out shear wave transmission measurements on austenitic welds and concluded that the columnar grains appeared to channel the waves into the root of the weld, so that the beam angle decreased as described by Singh. Beam skewing will bend shear wave beams towards the 0° direction, see Fig. 2. Silk(22) has commented on channelling by saying that there is no theoretical evidence that this will occur in weld metal like it does in some fibrous materials, since the acoustic impedance mismatch is not large between parallel dendrites and he also indicates that the tendency will be least for compression waves.

Gray et al(48) have reported errors in the location of side drilled holes (SDH) in 50 mm thick downhand MMA welds when using longitudinal waves. These errors were thought to be due to beam skewing and they were overcome by locating reflectors by a triangulation technique using two range values rather than one range value and a beam angle as shown in Fig. 3. The most unreliable component in the location of flaws in austenitic welds is the beam angle. Range values were found to be accurate and very close to the values measured in isotropic test blocks made from the same material despite the fact that compression wave velocities in austenitic weld metal can vary by 5% above to 10% below the isotropic value. The probable explanation is that beams tend to skew towards the high velocity directions in weld metal, therefore the longer beam path lengths for skewed beams are offset by the higher velocity value.

Holmes and Beasley,(6) Tomlinson et al(13) have reported bifurcation of ultrasonic beams in austenitic welds which complicates flaw location.

4.5.2 Flaw evaluation

(a) **Amplitude and probe movement techniques**

Amplitude and probe movement techniques for determining flaw sizes are deleteriously affected by anisotropy. Hudgell and Seed(46.47) concluded that it was impossible to construct a practical DAC curve for a compression wave inspection of 50 mm thick MMA austenitic welds. However, a practical DAC curve could be constructed for narrow gap welds with the same thickness. Neumann(55) et al has not reported any problems concerning the construction of DAC curves for the examination of austenitic welds when using T/R probes, however, Frielinghaus et al(57) have made some adverse comments. Tomlinson et al(13) comment that probe movement techniques for sizing flaws are not practical due to fluctuations in beam width. These fluctuations occur even when the beams are propagating along low attenuation paths. An obscuration technique was developed to size flaws in the Hartlepool and Heysham AGR Superheater closure welds.

Bell et al 1982(82) reported the results of destructive tests carried out on fourteen deliberately defective downhand MMA welds in 50 mm thick Type 316 plate to investigate the performance of ultrasonics and X radiography for detecting and sizing fabrication flaws. The specimens were all machined smooth and they were examined under laboratory conditions. The important conclusions were that no major flaws were missed, but several minor flaws were overlooked. Flaw sizes in the range 2 mm to 5 mm separate those flaws which cannot easily be detected from those that can. Bell also came to the same conclusion as Tomlinson that the dB drop method of sizing flaws in austenitic welds was impractical.

Surprisingly few authors have chosen to report results or comment on the problems of sizing flaws in austenitic welds. Edelmann(40) recommends that every opportunity should be taken to remove samples after locating flaws in order to collect data on the inspectability of austenitic welds.

(b) **Diffraction techniques**

Silk 1984(83) claims that time domain techniques based on the ultrasonic diffraction of compression waves can be used to locate and size flaws in thick section ferritic welds and refers to a fatigue crack in an austenitic weld. Compression waves are preferred since they are less prone to scatter. The approach favoured by Silk is based on transmission using two probes, which again reduces the effect of scatter. Diffraction techniques have an advantage over specular reflection for flaw detection, in that the amplitude of diffracted signals varies less with beam angle than specular reflected signals, but the former are usually much smaller than the latter. The diffraction technique has been studied theoretically by Ogilvy and Temple 1983.(84)

Silk(83) also describes a very sensitive method for recording diffraction signals. The rf A scan is digitised and recorded on a B scan display with a grey scale. Positive going peaks are shown as black, and negative going peaks as white, or vice versa. (An example is shown in Fig. 4.) With this type of display the relative phase of the diffracted signals can be determined. The two diffracted signals detected from the extremities of a buried planar flaw will be 180° out of phase, whereas the diffracted signals detected from two slag lines will have the same phase. Thus in theory, innocuous flaws can be distinguished from potentially dangerous ones. However, it should be pointed out that not all planar flaws behave in this way and the relatively low diffracted signal levels make noise signals more significant.

The theoretical model developed by Silk(22) (see Section 3.3) to check the relationship between crack depth and the time delay of diffracted signals in transversely isotropic materials predicted that the relationship was little different to that for isotropic materials. Experimental work has subsequently supported this prediction.

Silk(20) has reported the results of applying the technique to a 39 mm thick austenitic weld containing a fatigue crack which propagated into a fabrication flaw. Both flaws were sized to an accuracy of ±0·4 mm which is similar to the figures reported by Charlesworth et al 1978(85) for fine grain ferritic steels. Thus the technique is capable of high accuracy.

Some of the specimens described by Bell(82) were examined with the diffraction technique by Silk, and Fig. 4 shows the results obtained from one of these specimens containing a lack of sidewall fusion flaw. The diffracted signals from this can be seen in the lower left hand corner of Fig. 4. The depth scale has been linearised and each division represents 5 mm, whereas for the axial scale each division represents 20 mm. Sectioning revealed that the through thickness depth of the intended flaw was 3 mm, which was also the resolution of the ultrasonic system, yet the diffraction technique measured this precisely. However, a number of very small indications were detected by the diffraction technique which have not been revealed by sectioning. The first 10 mm of the specimen (from the top) was not examined as a probe spacing of 100 mm was selected which did not cover the near surface region.

The signal-to-noise ratio in Fig. 4 is low considering that the weld was made in the downhand position and therefore the compression wave beams should have followed low attenuation paths through the weld. Furthermore, the noise appears to be banded which suggests that it might be associated with weld beads. If this could be established it might provide a basis for a non-destructive technique to determine the weld structure as suggested by Bell et al.(82)

Dau and Behravesh 1983(86) report favourably on crack tip diffraction for sizing cracks in BWR pipework, while a few authors have reported the successful sizing of surface breaking and buried flaws associated with the stainless steel corrosion resistant cladding on PWR pressure vessels using diffraction techniques. Saitoh et al 1980(87) reports using dye penetrants to detect flaws and a 45° compression wave probe to measure their depth by the detection of the crack tip signal, but the authors do not explain how they recognise this. Rogerson et al 1984(88) and Charlesworth and Hawker 1984(89) describes the results of an investigation to test the ability of ultrasonic techniques to detect, size and characterise flaws in the first 30 mm of a ferritic PWR plate clad with 7 to 8 mm of stainless steel cladding. All the intended flaws were detected using compression wave 0° and 70° T/R probes. The dimensions of the flaws in the through thickness direction were measured by the diffraction technique using a pair of compression wave probes and the mean accuracy achieved for approximately twenty vertical flaws was + 0·6 mm. Charlesworth and Temple 1982(90) give a theoretical analysis of the application of the diffraction technique for sizing flaws in materials with anisotropic cladding.

Thus diffraction techniques have been successfully applied to austenitic cladding, and to austenitic weld metal, but relatively little has been published on the application of the technique.

5. DISCUSSION

5.1 General comments

Austenitic welds and castings usually have a strongly textured columnar grain structure and the special difficulties experienced in ultrasonic testing are due to their anisotropic properties which cause beam skewing and scattering of ultrasonic waves. Beam skewing does not occur in isotropic material such as ferritic weld metal, but scattering occurs in all polycrystalline materials, however it is far less severe in ferritic welds than it is in austenitic welds. For these reasons, austenitic welds will always be more difficult to examine than ferritic welds, but substantial improvements have been made in the inspection techniques employed for both types of welds in the last ten years. Thus there is reason to believe that careful choice of materials, geometrical factors and welding procedure at the design stage can permit a good sensitivity to be achieved for flaw detection, while very limited published data suggest that the time-of-flight diffraction technique can provide a good sizing capability in appropriate applications.

Perhaps the most optimistic view expressed recently is that of Mech,(71) 'that the existing technology is sound and only difficult engineering problems exist' for the high temperature ultrasonic inspection of the pipework of the Fast Flux Test Reactor.

The dependence of inspectability on detailed design and the welding procedure make it particularly difficult to codify the inspection procedures for austenitic welds or even to specify criteria by which their overall effectiveness may be satisfactorily tested. These factors are aggravated by the ultrasonic behaviour of some cast components which have to be joined and it is also found that the inspection reliability is particularly sensitive to equipment variations. These are all contributory factors to the unsatisfactory situation reported by Becker 1980,(91) Doctor et al 1982(92) and Taylor(73) for the effectiveness of ultrasonic examinations of Water Reactor pipework for the occurrence of IGSCC when such examinations were undertaken using the minimum requirements of Division 1 of Section XI of the ASME Boiler and Pressure Vessel Code.

It must also be recognised that in addition to the special difficulties discussed in the review, austenitic weld inspection is also subject to the normal problems of ultrasonic inspection associated with access, surface finish and flaw characteristics. In view of the lower capabilities of ultrasonic techniques for austenitic welds by comparison with ferritic welds, it is probably necessary to accept a smaller factor of safety between the smallest flaw that can be reliably detected and the largest flaw that is tolerable on safety or economic grounds.

5.2 Some areas where further work is required

5.2.1 Weld properties

There is a need to know more about the bulk properties of weld metal produced by different welding processes, and the effect of wide variations in composition should also be assessed. The objective of such an exercise might be to grade welding processes in terms of ultrasonic inspectability, and the following properties should be measured:

(i) Degree of anisotropy (velocity measurements).

(ii) Attenuation due to grain boundary scattering as a function of frequency.

Attenuation due to scattering is difficult to measure precisely due to skewing, but comparative measurements are possible. Very little work has been done on scattering in textured materials, probably because it is a difficult subject to tackle experimentally and theoretically.

5.2.2 Modelling

Much more needs to be known about how to examine austenitic welds and the most promising approach appears to be theoretical modelling along the lines described by Thomson and Farley(23) and by Ogilvy.(24) If their models can provide accurate information on the reflectivity of flaws in austenitic welds and the most suitable probes to detect them they would be very valuable tools. In particular models are essential to extrapolate from available experimental data to other situations.

5.2.3 Flaw detection and sizing

Methodical exercises are required to check the capabilities of ultrasonic techniques to detect and size flaws. The technique which appears to have the most potential for accurate sizing is the time-of-flight crack tip diffraction technique and a great deal of work needs to be done to explore the potential and limitations of this on all types of austenitic welds. Up to the present, published results of large scale studies of inspection reliability have been largely confined to the examination of LWR pipework for IGSCC.

5.2.4 EMATS

The wave mode which is least affected by the properties of transversely isotropic materials is Sh shear waves, and the potential advantage of being able to apply this wave mode on a routine basis to the inspection of austenitic welds is large. However, the only practical transducer which can be used to generate Sh waves is the EMAT, and these are very inefficient compared to piezo electric devices, but they are worth developing particularly for the inspection of poorly characterised welds in old plant.

5.3 Changes in welding practice

The area where the largest impact can be made on the difficulty of ultrasonically examining austenitic welds in new plant is in welding technology. If plant designers and fabricators were to develop and use narrow gap welding techniques on all austenitic components that may have to be inspected in-service, then the problem of examining them ultrasonically would eventually disappear.

Narrow gap welds have other attractions apart from being easy to inspect. For example, they have a higher toughness than welds made by the MMA process since they contain fewer inclusions, and they are obviously more economical in terms of consumables than conventional welds.

The ideal technique for examining narrow gap welds is the time-of-flight diffraction technique, since it would be practical to detect and size flaws with the one technique.

6. CONCLUSIONS

1. Austenitic welds and castings have a strongly textured columnar grain structure.
2. The symmetry of some austenitic weld metal has been found to be transversely isotropic.
3. The difficulties experienced in ultrasonic examination of welds and castings are due to their bulk anisotropic properties and also the large dimensions of their grains.
4. Anisotropy causes large variations in ultrasonic attenuation due to a beam skewing phenomenon and the magnitude of this depends on the elastic constants of the material, the wave mode and also the beam to grain angle.
5. Anisotropy and the large grain size causes scattering of ultrasonic waves and the magnitude of this is probably a complex function of many variables such as the dimensions of the grains, test frequency, beam to grain angle, wave mode, and the elastic constants of the material.
6. Further data is required on the properties of weld metal made by the different welding processes to supplement existing data on MMA weld metal.
7. The development of EMATs should be encouraged.
8. Theoretical modelling should be pursued so that a better understanding is obtained of the reflectivity behaviour of flaws in austentic weld metal, and the most suitable probes for detecting flaws.

9. More experimental data is required on the detection and sizing of flaws in austenitic weld metal.

10. Plant designers and fabricators should be encouraged to consider narrow gap welding techniques for austenitic components.

11. The general sensitivity of routine ultrasonic inspections undertaken on austenitic welds is lower than for ferritic welds but careful component design and fabrication, together with appropriate ultrasonic procedures, can yield considerable improvements.

7. REFERENCES

1. CAUSSIN, P. Ultrasonic testing of austenitic stainless steel structures, state of the art and progress report. Prepared for the CSNI Working Group on Safety Aspects of Steel Components in Nuclear Installations. 1978

2. WHITAKER, J. S. and JESSOP, T. J. Ultrasonic detection and measurement of defects in stainless steel – A literature survey. British Journal of NDT, Vol. 23, No. 6, pp 293-303, November 1981

3. LOTT, L. A. and MALIK, R. K. Ultrasonic inspectability improvements in austenitic stainless steel welds after thermal-mechanical processing. Materials Evaluation, 41, pp 738-742, May 1983

4. ALBERRY, P. J., ROWLEY, T. and YAPP, D. Control of manual metal-arc weld quality by deposition sequence. 4th Int. Conf. Advances in Welding Processes, Harrogate, 9-11 May 1978

5. BAIKIE, B. L. and YAPP, D. Orientated structures and properties in Type 316 stainless steel weld metal. Proc. Int. Conf. on Solidification and Casting, Sheffield, p 438-443, published by the Metals Society of London, 1979

6. HOLMES, E. and BEASLEY, D. The influence of microstructure in the ultrasonic examination of stainless steel welds. J. of Iron and Steel, Vol. 200, Part 4, p 283, April 1962

7. SALTMUTTER, K. and STANGLER, F. Eine elastizitat und plasticitat eines austenitischen chrom-nickel stahls. Zeits. F Metallkunde 51, No. 9, pp 544-548, 1960

8. HOLMES, E. Ultrasonic behaviour in austenitic stainless steel. Applied Materials Research, p 181-184, July 1963

9(a) PETERSON, R. O., SPANNER, J. C. and MECH, S. J. Development of UT methods for examining stainless steel welds. HEDL-TME-75-134, November 1975

9(b) BAIKIE, B. L., WAGG, A. R., WHITTLE, M. J. and YAPP, D. Ultrasonic inspection of austenitic welds. Journal of British Nuclear Energy Society, **15** (3), 257-261, July 1976

10. MUSGRAVE, M. J. P. On the propagation of elastic waves in aeolotropic media. I General principles. Proc. Roy. Soc. A., 226, p 339-355, 1954

11. MUSGRAVE, M. J. P. On the propagation of elastic waves in aeolotropic media. II Media of hexagonal symmetry. Proc. Roy. Soc. A, 226, p 356-366, 1954

12. MILLER, G. F. and MUSGRAVE, M. J. P. On the propagation of elastic waves in aeolotropic media. III Media of cubic symmetry. Proc. Roy. Soc. A, 236, p 352-383, 1956

13. TOMLINSON, J. R., WAGG, A. R. and WHITTLE, M. J. Ultrasonic inspection of austenitic welds. Proc. Int. Conf. Nondestructive Evaluation in the Nuclear Industry, Salt Lake City, Utah, USA, 13-15 February 1978. American Society for Metals, pp 64-83

14. ADLER, L., COOK, K. V., SIMPSON, W. A., LEWIS, D. K. and FITTING, D. W. Ultrasonic flaw detection and characterisation in structural materials by spectral analysis. ORNL/TM-6456, 1978. Dept. of Energy, Technical Information Centre, P.O. Box 62, Oak Ridge, Tennessee 37830

15. GILLAN, M. T. Ultrasonic wave propagation in austenitic stainless steel weld metal. Theoretical Physics Dept. Report TP839, May 1980, Atomic Energy Research Establishment, Harwell, UK

16. KUPPERMAN, D. S. and REIMANN, K. J. Ultrasonic wave propagation and anisotropy in austenitic stainless steel weld metal. IEEE Transactions on Sonics and Ultrasonics, Vol. SU-27, No. 1, January 1980

17. JUVA, A. and LENKKERI, J. The effects of anisotropy on the propagation of ultrasonic waves in austenitic stainless steel. Proceedings of Specialists Meeting on Reliability of Ultrasonic Inspection of Austenitic Stainless Steel Components, Brussels, CSNI Report 46, pp 2-24, May 1980

18. CURTIS, G. J. and IBRAHIM, N. Texture studies of austenitic weld metal using elastic surface waves. Metal Science, Vol. 15, pp 566-573, November-December 1981

19. AULD, B. A. Acoustic fields and waves in solids. Two volumes. John Wiley and Sons, New York. 1973

20. SILK, M. G. Ultrasonic techniques for inspecting austenitic welds. Chapter 11. Research Techniques in Non-destructive Testing, Vol. IV, Ed. R. S. Sharpe, Academic Press, London, New York, etc. 1980

21. KUPPERMAN, D. S. and REIMANN, K. J. Visualisation of ultrasonic beam distortion in anisotropic stainless steel. Proc. Int. Conf. on Quantitative NDE in the Nuclear Industry, San Diego, Ed. R. B. Clough, ASM published. 1983

22. SILK, M. G. A computer model for ultrasonic propagation in complex orthotropic structures. Ultrasonics, pp 208-212, September 1981

23. THOMSON, J. L. and FARLEY, J. M. Ultrasonic examination of austenitic welds: Theoretical and practical considerations. Presented at 6th Int. Conf. on NDE in the Nuclear Industry, Zurich, Switzerland, 28 November-2 December 1983

24. OGILVY, J. A. Identification of pulse-echo rays in austenitic steels. NDT International, Vol. 17, No. 5, October 1984, pp 259-264

25. GOEBBELS, K. Materials characterisation. Proc. of 1st Int. Symposium on Ultrasonic Materials Characterisation. NBS Gaithersburg Md, 7-9 June 1978. National Bureau of Standards Special Publication, 596, pp 37-40

26. GREEN, R. E. Effect of metallic microstructure on ultrasonic attenuation. Proc. of a Symposium on Microstructural Characterisation and Reliability Strategies. Pittsburg, Pennsylvania, 5-9 October 1980

27. SHYNE, J. C. Acoustic properties as microstructure dependent materials properties. Proc. of Symposium on Microstructural Characterisation and Reliability Strategies, Pittsburg, Pennsylvania, 5-9 October 1980

28. PAPADAKIS, E. M. Chapter 15 Ultrasonic attenuation caused by scattering. Physical Acoustics Principles and Methods, Vol. IV, Part B. Applications to Quantum and Solid State Physics, Ed. Warren P. Mason, Academic Press. 1968

29. LIFSHITZ, E. M. and PARKHAMOVSKII, G. D.Zh. Ek sperim. i Teoret. Fiz 20, p 175-182, 1950

30. MERKULOV, L. G. Soviet Phys. – Tech. Phys (English Transl) 1, 59-69; Zh Tekh. Fiz 26, 26-75, 1956

31. RAYLEIGH LORD 1894. The theory of sound, pp 149-152, MacMillan, New York and Dover. New York (First Am. Ed, 1945)

32. PAPADAKIS, E. M. Revised grain-scattering formulas and tables. J. Acoustic Soc. of Am., Vol. 37, No. 4, p 703-710, April 1965

33. MASON, W. P. and McSKIMIN, H. T. J. Appl. Phys. 19, pp 940-946, 1948

34. GOEBBELS, K. and HOLLER, P. Quantitative determination of grain size and detection of inhomogeneities in steel by ultrasonic backscatter measurements. National Bureau of Standards Special Publication 596. Proc. of the First Int. Symposium on Ultrasonic Materials Characterisation, Gaithersburg, 7-9 June 1978

35. PAPADAKIS, E. M. Influence of preferred orientation on ultrasonic grain scattering. J. Appl. Phys. 36, p 1738-1740, 1965

36. MORSE, P. M. Vibration and sound. 2nd Ed. McGraw Hill, New York, pp 346-357, 1948

37. ERMOLOV, I. N. and PILIN, B. P. Ultrasonic inspection of materials with coarse grain anisotropic structures. NDT International, pp 275-280, December 1976

38. KUPPERMAN, D. S. and REIMANN, K. J. Effect of shear wave polarisation on defect detection in stainless steel weld metal. Ultrasonics, January 1978

39. JUVA, A. and LIETO, A. The ultrasonic examination of thin austenitic stainless steel butt welds. British Journal of NDT, July 1980

40. EDELMANN, X. Application of ultrasonic testing techniques on austenitic welds for fabrication and in-service inspection. NDT International, pp 125-133, June 1981

41. IBRAHIM, S. I., KAPRANOS, P. A. and WHITTAKER, V. N. Ultrasonic inspection of fatigue cracks in the HAZ of austenitic weldments using shear wave probes. British Journal of NDT, pp 65-74, March 1982

42. KAPRANOS, P. A. and WHITTAKER, V. N. Ultrasonic inspection of fatigue cracks in austenitic 316 and 347 weldments. British Journal of NDT, pp 129-133, May 1982

43. KAPRANOS, P. A. Compression crack closure effect (CCCE) – A basis for an ultrasonic NDE technique. Materials Evaluation, pp 458-462, April 1984

44. TRUMPFF, B., LAUNAY, J. P. and OLIVERA, J. J. Contribution to improving ultrasonic testing of thick bimetallic welds. CSNI Report No. 46, 1980

45. SANDBERG, S. Report on a survey of ultrasonic testing in austenitic weld material. CSNI Report No. 46, 1980

46. HUDGELL, R. J. and SEED, H. Ultrasonic longitudinal wave examination of austenitic welds. British Journal of NDT, pp 78-85, March 1980

47. HUDGELL, R. J. and SEED, H. The inspection of austenitic butt welds by longitudinal ultrasonic waves. 4th Int. Conf. Pressure Vessel Technology, I.Mech.E., 19-23 May 1980. London, Vol. II, C97/80, pp 269-276

48. GRAY, B. S., HUDGELL, R. J. and SEED, H. Longitudinal wave ultrasonic inspection of austenitic weldments. Proceedings of the Specialists Meeting on Reliability of the Ultrasonic Inspection of Austenitic Materials, Brussels. CSNI Report No. 46, pp 150-168, May 1980

49. GOEBBELS, K. and KAPITZA, H. Methods for nondestructive testing of austenitic high temperature gas cooled reactor components. Nuclear Technology, Vol. 66, pp 695-702, September 1984

50. KRAUS, S. and GOEBBELS, K. Improvement of signal-to-noise ratio for the ultrasonic testing of coarse grained materials by signal averaging techniques. National Bureau of Standards Special Publication 596, June 1978

51. HEINRICH, D., MULLER, G. and WEISS, M. Mechanised in-service ultrasonic inspection of austenitic welds in nuclear plants. NDT International, pp 170-184, August 1982

52. NEUMANN, E., ROEMER, M., SCHENK, R. and MATTHIES, K. On the applicability of ultrasonic testing techniques for coarse grain austenitic welds. CSNI Report No. 46, May 1980

53. OPPERMAN, W. and CROSTACK, H. A. Some fundamental aspects of testing austenitic steel structures by ultrasonics. CSNI Report No. 46, May 1980

54. NEUMANN, E., KUHLOW, B., ROMER, M. and MATTHIES, K. Ultrasonic testing of austenitic components of sodium cooled fast reactors. Proceedings of a specialists meeting on the in-service inspection and monitoring of LMFBR's, IAEA, Bensberg, Germany, March 1976. IWGFR/10, pp 57-71

55. NEUMANN, E., ROEMER, M., SCHENK, R. and NABEL, E. Status of ultrasonic testing techniques for austenitic coarse grained weld joints. Proc. 9th World Conf. on NDT, Melbourne, 1979

56. GANGLBAUER, O., WALLNER, F. and FRIELINGHAUS, R. Contribution to the ultrasonic testing of austenitic welds using longitudinal angle-beam probes. Proc. 9th World Conf. on NDT, Melbourne, 1979

57. FRIELINGHAUS, R., GANGLBAUER, O. and WALLNER, F. The evaluation of the amplitude when testing austenitic welded joints ultrasonically. Proc. 9th World Conf. on NDT, Melbourne, 1979

58. JURENKA, H. J. Development of the ultrasonic technique for examination of centrifugally cast stainless steel in pressure piping. Proc. Int. Conf. on Quantitative NDE in the Nuclear Industry, San Diego. Ed. R. B. Clough, ASM, 1983

59. ROSE, J. L. and ROGOVSKY, A. J. Austenitic stainless casting inspection potential. Presented at First Int. Symposium on Ultrasonic Materials Characterisation, Gaithersberg Md, June 1978. National Bureau of Standards Special Publication 596, Ed. H. Berger, M. Linzer

60. EDELMANN, X. and HORNUNG, R. Investigation of an ultrasonic technique for detection of surface flaws during in-service inspection of dissimilar metal welds. Proc. 5th Int. Conf. on Quantitative NDE in the Nuclear Industry, San Diego, California, 10-13 May 1982. American Society for Metals

61. ERMOLOV, I. N., RAZYGRAEV, N. P. and SHERBINSKII, V. G. The use of head-type-acoustic waves for ultrasonic monitoring. Soviet Journal of NDT, Vol. 14, No. 1, pp 27-33, 1978

62. GRUBER, G. J., HENDRIX, G. J. and SCHICK, W. R. Characterisation of flaws in piping welds using satellite pulses. Materials Evaluation, Vol. 4, pp 426-432, April 1984

63. ELSLEY, R. K. and FORTUNKO, C. M. Improvements in flaw detection in austenitic stainless steel weldments. Ultrasonic Symposium, pp 892-899, 1981. National Bureau of Standards

64. FORTUNKO, C. M. and MOULDER, J. C. Ultrasonic inspection of stainless steel butt welds using horizontally polarised shear waves. Ultrasonics, pp 113-117, May 1982

65. MURALI, M. K. and NEELAKANTAN, K. Improved ultrasonic flaw detection technique for austenitic stainless steel welds. NDT International, pp 321-324, December 1981

66. NEWHOUSE, V. L., BILGUTAY, N. M. and SANIIE, J. Flaw to grain echo enhancement by split spectrum processing. CSNI Report No. 46, 1980

67. DAY, R. A. A method of assessing the impact of metallurgical noise and its reduction in ultrasonic testing of austenitic welds. Proc. IEEE Ultrasonic Symposium, 26-28 September 1979

68. MUCCIARDI, A. N. Automatic detection and sizing of intergranular stress-assisted corrosion cracks from ultrasonic RF signal analysis. 3rd Int. Conf. on NDE in the Nuclear Industry, Salt Lake City, 1980. American Society for Metals

69. ROSE, J. L., AVIOLI, M. J. and LAPIDES, M. E. Utilisation of a Fisher linear discriminant function in IGSCC detection. CSNI Report No. 46, 1980

70. JUSINO, A. and ADAMONIS, D. C. Improvements of the ultrasonic inspection of the centrifugally cast stainless steel pipe weldments by Adaptive Learning Network. Proc. Int. Conf. on Quantitative NDE in the Nuclear Industry, San Diego. Ed. R. B. Clough, pp 443-448, 1983

71. MECH, S. J. Ultrasonic test data acquisition and defect verification of stainless steel welds at 400°F. HEDL-SA-2895-FP, 1983

72. SHANKAR, R. and MUCCIARDI, A. N. Application of Adaptive Learning Networks to ultrasonic signal processing – detecting cracks in stainless steel pipe welds. Proc. of 1st Int. Symposium on Ultrasonic Materials Characterisation. NBS Gaithersburg, June 1978. National Bureau of Standards Special Publication 596

73. TAYLOR, T. An evaluation of manual ultrasonic inspection of cast stainless steel piping. Prepared for US Nuclear Regulatory Commission, May 1984. NUREG/CR-3753, PNL-5070. Pacific NW Laboratory

74. TOMLINSON, J. R. and WAGG, A. R. Experience in ultrasonic inspections of fillet and butt welds in austenitic steel in Heysham and Hartlepool AGR's. CSNI Report No. 46, May 1980

75. WAGG, A. R. and WHITTLE, M. J. A specification for ultrasonically inspecting the superheater head to thermal sleeve welds at Heysham and Hartlepool power stations. CEGB Report No. NW/SSD/SR/100/78, September 1978

76. MACECEK, M. Metallurgical causes of difficulties with ultrasonic inspection of austenitic welds. ASME Paper 78-PVP-8. 1978

77. KUPPERMAN, D. S., REIMANN, K. J. and KIM, D. I. Ultrasonic characterisation and microstructure of stainless steel weld metal. Proc. of Symposium on Microstructural Characterisation and Reliability Strategies, Pittsburg, Pennsylvania, 5-9 October 1980

78. WAGG, A. R. The non-destructive testing of transition welds. IAEA Specialists Meeting on In-service Inspection and Monitoring of LMFBR's, Bensberg, 20-22 May 1980. IWGFR/35

79. SINGH, A. Flaw location errors in extruded stainless steel piping. Ultrasonics, pp 270-274, November 1983

80. PADAKI, V. C., BARAT, P., BALDEV, R. A. J. and BHATTACHARYA, D. K. Ultrasonic inspection of austenitic stainless steel weldments – our experiences. IIW Doc. VC-432-84. 1984

81. YONEYAMA, H., SHIBATA, S. and KISHIGAMI, M. Ultrasonic testing of austenitic stainless steel welds. Proc. 9th World Conf. NDT, Melbourne, November 1979

82. BELL, I. P., GRAY, B. S., HUDGELL, R. J. and SARGENT, T. H. Reliability assessment of austenitic steel ultrasonic inspections – progress report on a UKAEA programme. Advances in Non-Destructive Examination for Structural Integrity. Ed. R. W. Nichols. Applied Science. 1982

83. SILK, M. G. Measurements to locate and size defects. Brit. J. of NDT, pp 208-213, May 1984

84. OGILVY, J. A. and TEMPLE, J. A. G. Diffraction of elastic waves by cracks: application to time-of-flight inspection. Ultrasonics, Vol. 21, No. 6, pp 259-269, November 1983

85. CHARLESWORTH, J. P., SILK, M. G. and LIDINGTON, B. H. Defect sizing using ultrasonic flaw diffraction. Proc. of the 1st European Conf. on NDT, Mainz, 1978. DGfZP, Vol. 1, pp 55-62

86. DAU, G. J. and BEHRAVESH, M. Status of intergranular stress corrosion crack depth sizing. Presented at 3rd Int. Seminar on 'NDE in Relation to Structural Integrity', Monterey, August 1983

87. SAITOH, T. and TAKAHASHI, S. Sizing of cracks perpendicular to stainless steel overlay by ultrasonic testing. CSNI Report No. 46, May 1980

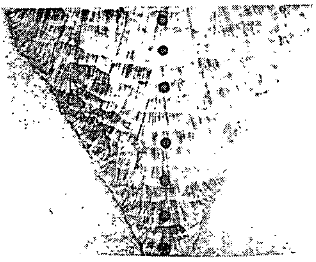
88. ROGERSON, A., POULTER, L. N. J., DYKE, A. V. and TICKLE, H. Inspection of defect detection trials plate 3 by the Materials Physics Department, RNL. Brit. J. of NDT, pp 20-26, January 1984

89. CHARLESWORTH, J. P. and HAWKER, B. M. Inspection of the near-surface defect plate (DDT3) by the ultrasonic time-of-flight technique. Brit. J. of NDT, Vol. 26, No. 2, February 1984

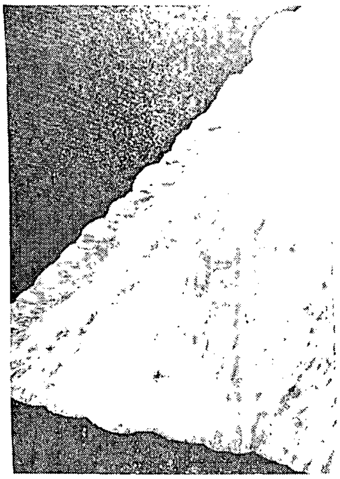
90. CHARLESWORTH, J. P. and TEMPLE, J. A. G. Ultrasonic time-of-flight inspection through anisotropic cladding. Proc. Conf. on Periodic Inspection of Pressurised Components, London, October 1982. I.Mech.E., p 117-124

91. BECKER, F. L. Ultrasonic inspection reliability for primary piping systems. Proceedings of the Specialists Meeting on Reliability of the Ultrasonic Inspection of Austenitic Materials, Brussels, May 1980. CSNI Report No. 46, pp 456-480

92. DOCTOR, S. R., BECKER, F. L. and SELBY, G. P. Effectiveness and reliability of US in-service techniques. Periodic Inspection of Pressurised Components, I.Mech.E., London, pp 281-294, 1982.

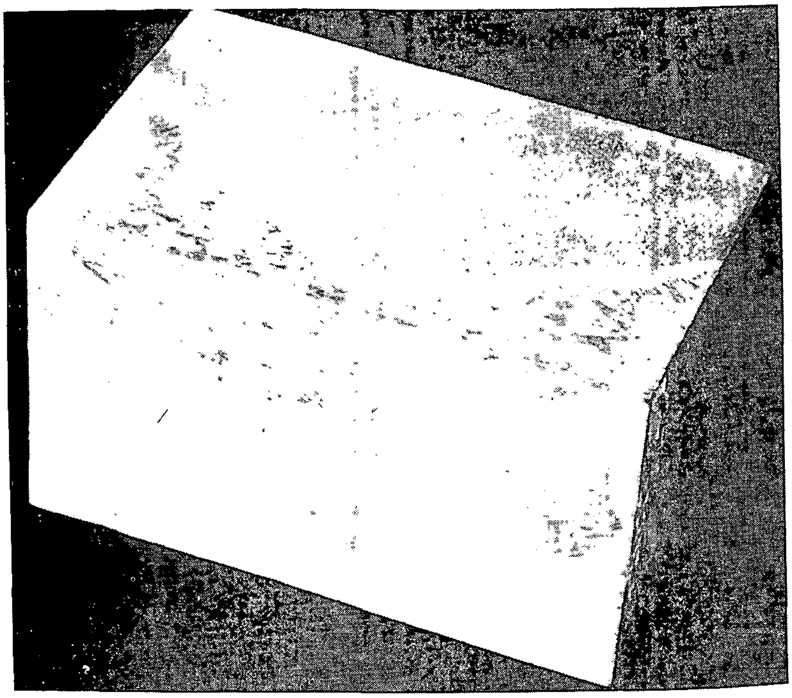


DOWNHAND WELD



(b)

HORIZONTAL-VERTICAL WELD



(c)

VERTICAL-UP WELD

FIG 1. MACROGRAPHS SHOWING COLUMNAR GRAINS IN MMA WELDS

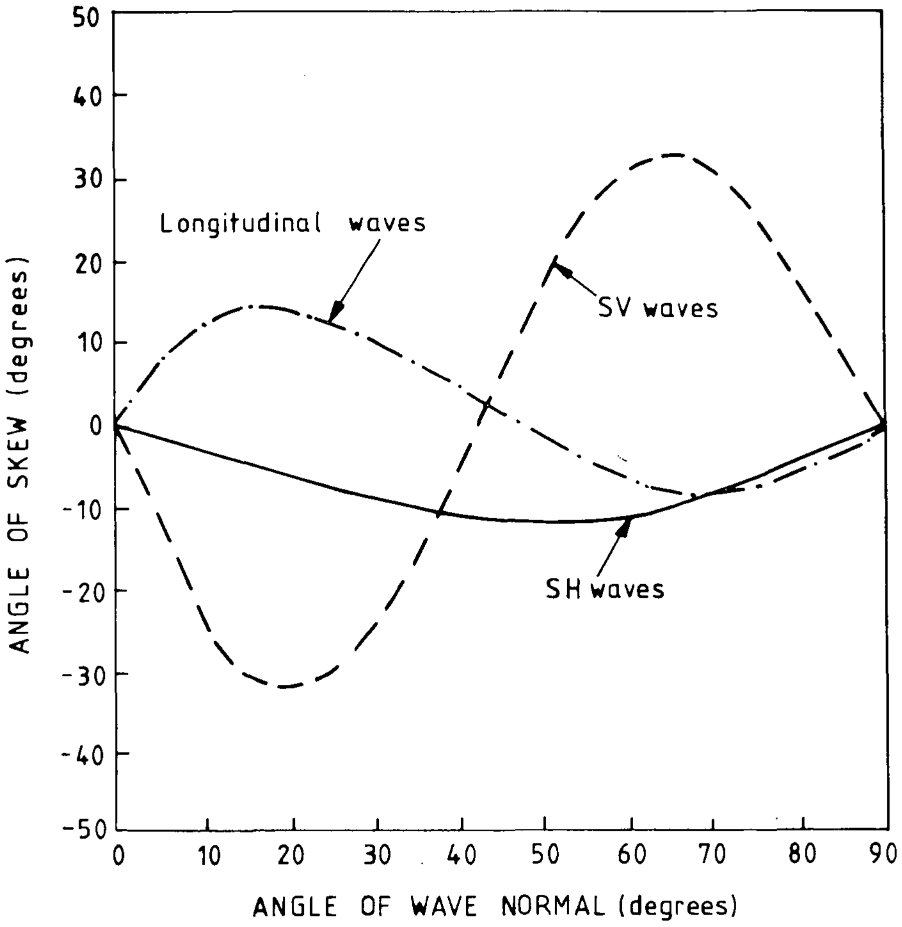


FIG.2 THE VARIATION OF SKEW WITH BEAM TO GRAIN ANGLE IN TRANSVERSELY ISOTROPIC STEEL. (AFTER SILK 1980)

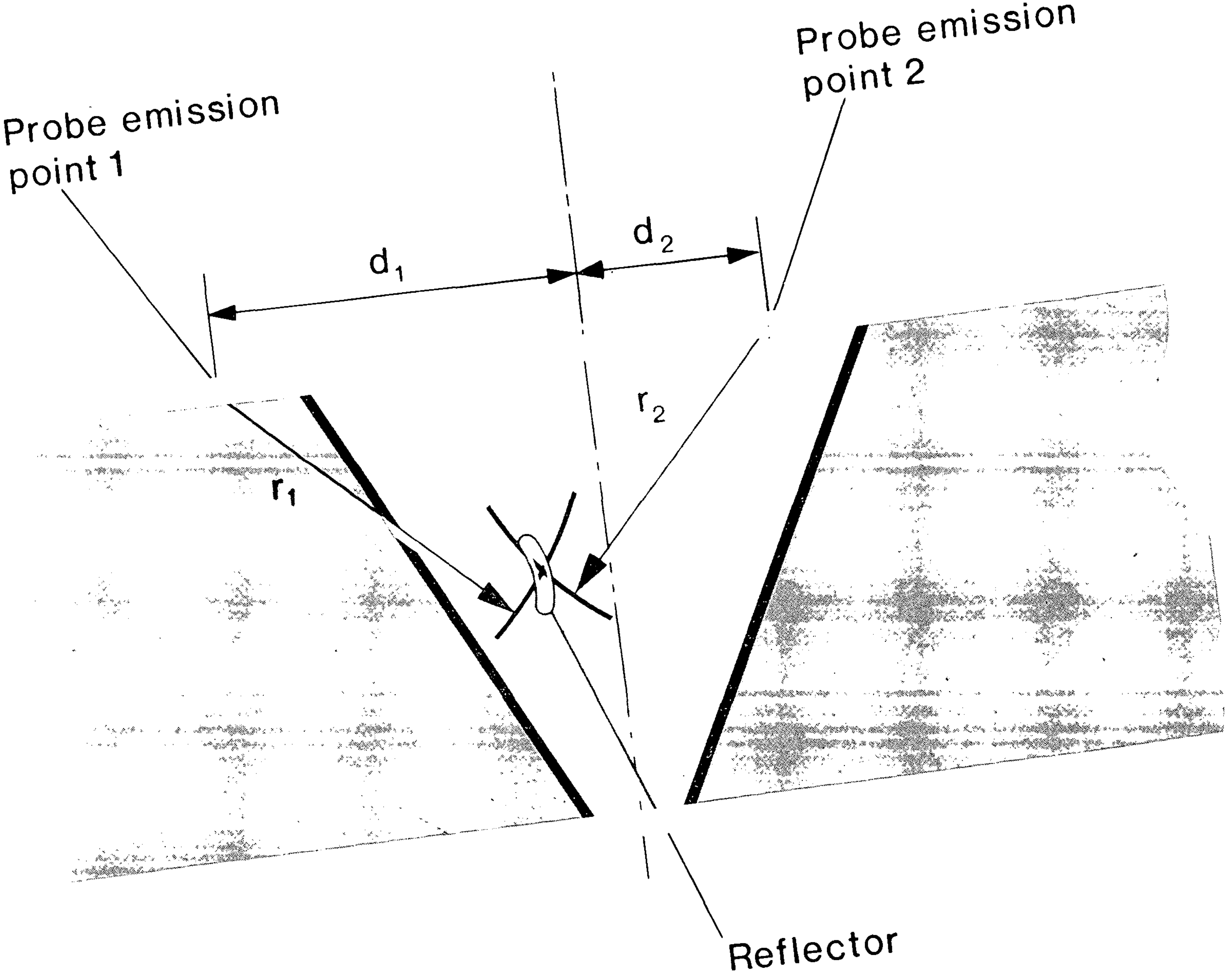


FIG 3. LOCATING A REFLECTOR IN AUSTENITIC WELDS USING ANGLED LONGITUDINAL

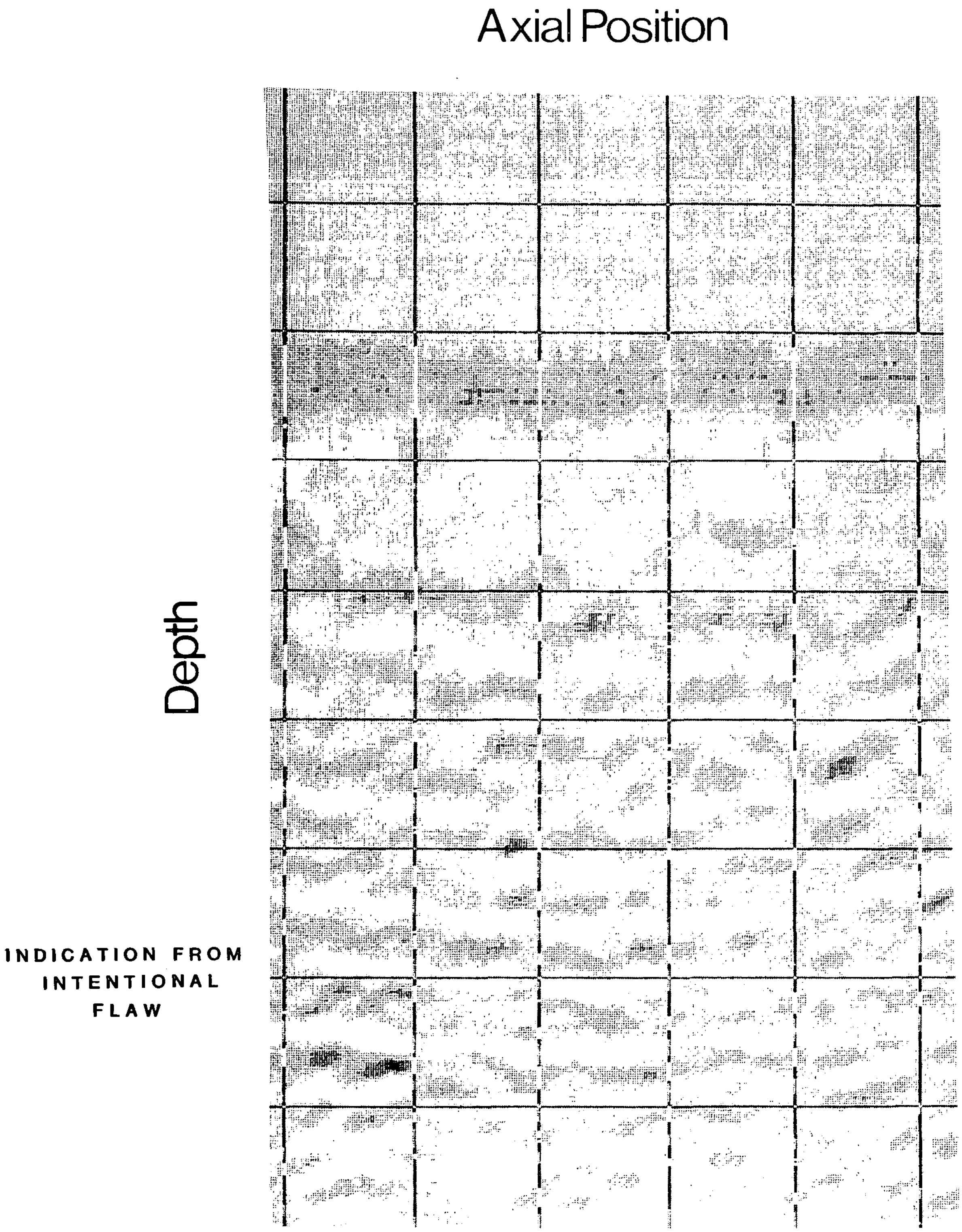


FIG 4. TIME OF FLIGHT DIFFRACTION DATA OF SILK FOR A DOWNHAND MMA WELD CONTAINING A LACK OF FUSION FLAW