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Handbook on the Ultrasonic Examination of Austenitic and Dissimilar Metal Welds

Compiled by a Working Party under the Leadership of Gérard HENNAUT, Vincotte, Belgium

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HANDBOOK ON THE ULTRASONIC EXAMINATION OF AUSTENITIC AND DISSIMILAR WELDS

DRAFT 14 (06 2005) of the 2nd Edition, to be reviewed by the WG members and to be propoded for publication after approval

List of working group members

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The working group wishes to acknowledge valuable contributions by other members of the companies' mentioned.

The handbook represents the agreed view of the working group experts but has not necessarily been endorsed by the individual organisations represented.

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FOREWORD

This handbook has been produced by the Working Group *"Ultrasonic Testing of Austenitic Welds"* of the IIW - Commission V_C Ultrasonics.

This is the second edition of the handbook which was first published in 1986. Since then, there has been some progress in understanding the underlying difficulties associated with the detection and the sizing of flaws in austenitic weld metal and this is included in this edition.

In addition, the scope of the second edition has been increased to include:

- inspection of dissimilar-metal welds and duplex materials
- in-service inspection
- the common types of flaws which occur during fabrication and service in austenitic welds
- benefit to be derived from the use of horizontally polarised shear waves for the inspection of columnar grained material.

Apart from the first edition, this handbook has been based on a similar handbook published in 1994 on the ultrasonic inspection of cladding and clad components. The theoretical aspects of ultrasonic propagation in austenitic weld metal are similar to those described for cladding in the cladding handbook.

This handbook covers the ultrasonic inspection of austenitic butt welds. However, the guidelines and recommendations are relevant to welds of most configurations.

The objective of the handbook is to inform all those involved in the volumetric examination of austenitic welds of the limitations caused by the acoustic properties of the material. The handbook is intended to provide guidance for the preparation of procedures for specific applications, but does not provide a detailed inspection procedure for any particular weld. The handbook is addressed to technicians, engineers and scientists involved in austenitic weld inspection. It should be of particular value to those responsible for preparing inspection procedures.

1 INTRODUCTION

Scope and objectives of handbook

The objective of the handbook is to provide ultrasonic operators, inspection engineers and scientists with the background knowledge necessary to perform effective ultrasonic inspections of austenitic welds. It is assumed that the reader is familiar with ultrasonic inspection of ferritic welds.

This handbook deals mainly with butt welds but the theory and practice presented can be applied to welds with more complex geometries providing that the additional difficulties of the geometry are taken into account. The handbook also covers dissimilar-metal welds, which are generally more difficult to examine than a straight butt weld due to the buttering layer.

The scope of the handbook includes fabrication and inservice inspections. The detection and sizing of fabrication and service-induced flaws are also discussed but the handbook does not contain acceptance criteria.

Structural characteristics of austenitic weld materials

The term “austenitic” applies to steels in which iron is predominantly present in the form known to metallurgists as “austenite”. These include a range of nickel-chromium steels used for high-temperature and corrosion-resistant applications. A typical composition for an austenitic steel would be 18% chromium and 8% nickel.

In contrast, low-alloy steels are described as “ferritic” since iron is in the form of “ferrite”.

While welds in ferritic steels may be inspected effectively by standard ultrasonic techniques, inspection of welds in austenitic steels is more difficult and requires special techniques. This is explained by the difference in the grain structure of welds in the two types of steel. In both cases, the molten weld metal solidifies as austenite giving a grain structure characterised by large crystals whose crystallographic axes lie in preferred orientations relative to the weld. In ferritic welds, the austenite is transformed into ferrite as the weld cools and the initial grain structure is replaced by one with smaller grains in a wider range of orientations. In typical multi-run welds, the deposition of successive runs causes the weld metal to undergo this transformation repeatedly and the end result is a structure in which the grain size is very small and the grain orientation is random.

In austenitic welds however, the austenite-ferrite transformation does not occur as the weld cools so that the initial grain structure remains fixed. Furthermore, in multi-run welds, the deposition of successive runs may cause many of the grains to grow resulting in long, columnar grains which may span a large fraction of the weld thickness.

This fundamental difference in grain structure has a profound effect on the propagation of ultrasound through the weld. All crystalline materials have physical properties - in particular the velocity of ultrasound - which vary with direction relative to the crystal lattice. In ferritic weld material however, the small size (in relation to the ultrasound wavelength) and the random orientation of the grains means that such variations are averaged out so that ultrasound velocity is the same in all directions; such material is said to be “isotropic”. In austenitic weld material, where the grains may have dimensions of many wavelengths and where the grain orientations are not random, the variation in velocity with direction relative the crystal axes of the grains becomes apparent; such material is said to be “anisotropic”. Anisotropy leads to a variety of effects which are described in this handbook. These include the deviation of ultrasound beams from their intended directions and high levels of attenuation and scattering. Much of the handbook is concerned with describing techniques which minimise the adverse impact of these effects on the effectiveness of ultrasonic inspection.

Grain structures similar to those found in austenitic welds are commonly found in other metals and similar difficulties with ultrasonic inspection may be encountered. There are however, significant variations in the degree of anisotropy of different metals so that each case requires separate consideration; but in general, the principles described in the handbook are applicable.

Steel piping systems often incorporate components of nickel alloys such as Inconel™ and Incalloy™. Welds in these materials generally have ultrasonic propagation characteristics similar to those of austenitic steel weld metal and the guidelines given in the handbook are valid for inspection of these welds.

Inspection of austenitic welds

The standard techniques used for ultrasonic inspection of ferritic welds are generally based on a combination of « straight-beam » examination with longitudinal waves and angle-beam examination with transverse-waves. These techniques are most commonly applied using ultrasound frequencies in the range from 1MHz to 5MHz. As explained in the handbook, if austenitic weld metal is to be inspected, these techniques have to be replaced by angle-beam examination with longitudinal waves and at frequencies not much greater than 2MHz.

While angle-beam examination with longitudinal waves will often provide acceptable inspection capability, it is important to realise that the predictions which can be made for the performance of inspections of ferritic welds cannot be made for austenitic weld inspection. When examining ferritic welds, accurate predictions can be made about the angle, width and sensitivity of an ultrasonic beam. In austenitic welds, these parameters depend on the relationship between the beam and the weld grain structure. Since the grain structure (i.e. the size and orientation of the grains) varies across the weld, and since that variation inevitably has a random component, the parameters of the beam vary from their nominal values in ways that cannot be predicted precisely.

Knowledge of the general pattern of the weld grain structure does enable useful predictions to be made as to the likely behaviour of ultrasound beams passing through the weld. Since different welding procedures result in different grain structures, it is important to know as much as possible about how the weld was made when writing a procedure to inspect it. With this knowledge it should be possible to produce an effective procedure. The capability of the procedure can, in the current state of the art, only be properly assessed by performing practical measurements to confirm that the flaws of interest can be detected, located and characterised.

Theoretical models can provide guidance at different stages of the process.

2 PARENT MATERIAL AND WELD STRUCTURE

In this section, the grain structures of austenitic welds are considered in more detail. The grain structures typical of welds made by the principal welding processes are described and the important influence of welding position is explained. The resulting structures may be disturbed by repair welding

Special consideration is required for dissimilar metal welds, given that these often require the highest level of inspection but that they have more complex grain structures than plain butt welds, making them more difficult to inspect.

Finally, a brief account of duplex welds is given.

Before describing weld grain structures, however the properties of the parent material are reviewed. These are very important. In some cases, the parent material is effectively transparent to ultrasound (at the frequencies applicable to austenitic weld testing). In other cases, the parent material effectively prevents ultrasound to reach the weld.

Parent Material Properties

In most cases, the parent material of at least one side of an austenitic weld is made from austenitic steel, which can be forged, rolled or cast. The extent to which the parent material properties affect the ultrasonic inspection can be much more severe for austenitic materials than for ferritic steel.

This section reviews the range of material properties that may be encountered.

Wrought Materials

The degree of anisotropy alone is not a measure of the sound transmittability of austenitic material. The average grain size plays also an important role. The sound scattering is a function of the ratio wavelength λ to grain size. It decreases as the probe frequency decreases. Typically, sufficient signal/noise ratios are obtained if the grain diameter is equal or less than 0.2λ. That means, for an inspection with a 2 MHz shear wave, that the acceptable average grain diameter is 0.4 mm.

The austenitic parent material frequently no longer possesses the coarse grain structure because, during the forming process, a re-crystallisation structure develops or is produced by subsequent re-crystallisation annealing. Therefore, in austenitic forged and plate material, the same flaw detectability can be reached as for ferritic steel.

Cast Materials

Castings have large grains, the size and structure of which, depends upon several features of the casting such as:

- chemical composition
- casting process (statically or centrifugally cast)
- pouring conditions (particularly temperature)
- size of casting

Both columnar and equiaxed grain structure may occur and these have different properties which must be taken into account in designing inspection techniques.

The structure is very hard to predict and even to be reproduced for large components. For this reason, it is always difficult to have representative castings to be used for validation and modelling is not easy.

In any case, the examination is always difficult when the beam passes through cast material to reach the weld and the validation of the procedure is difficult to establish.

Welding Process

The properties of steels can be changed and improved by applying an appropriate heat treatment. For instance, a grain refinement can be achieved by normalising a coarse ferritic structure. This cannot be done with austenitic steel, where any subsequent heat treatment does not reduce the grain size. The original grain size is kept, which can mean relatively long grains between 0,5 mm and a few millimetres in the through wall direction.

The weld metal crystallises in the form of so-called dendrites. Dendrites are columnar grains with a preferential orientation in the direction of the temperature gradient. The grain growth depends upon the parent and filler metals, the welding method and its parameters, but also on the shape and thickness of the weld. The columnar grains are oriented roughly perpendicular to the surface of the weld preparation or to the weld runs. In the case of austenitic steel, they can pass through several runs (epitaxial growth) and extend up to the surface.

The basic parameters that affect ultrasonic inspection are material grain size and grain orientation. The latter has the largest influence on the choice of ultrasonic techniques such as wave mode and beam angle.

The characteristic structure of austenitic welds is columnar grains, which can in some cases extend the full thickness of the weld. The principal factors that control the grain angle distribution within the weld are:

- the welding process
- the welding position
- the shape of the weld fusion face

The following sections describe the basic principles that determine the grain angle distribution and how different welding types influence these principles. All factors are to be considered together. Prediction is not easy and a macrograph of a weld made under the same conditions can be very useful.

Grain Angle Distribution

When a weld bead is laid down on top of a previous one, there is a partial melting of the original bead. During solidification, the resulting grains are continuous across the fusion face between the weld beads. This epitaxial grain growth then extends across several weld beads and thereby gives the characteristic columnar grain structure.

The grain angle distribution in a volume of austenitic weld metal is determined predominantly by the direction of the heat flow as each weld bead solidifies. When weld metal is deposited on a flat weld preparation, heat flows in a direction perpendicular to the parent surface. Consequently, the grain direction adjacent to a weld fusion face is perpendicular to the fusion face (Figure 1). As subsequent weld beads are laid down, the direction of heat flow changes and hence the grain angle deviates from being normal to the weld fusion face.

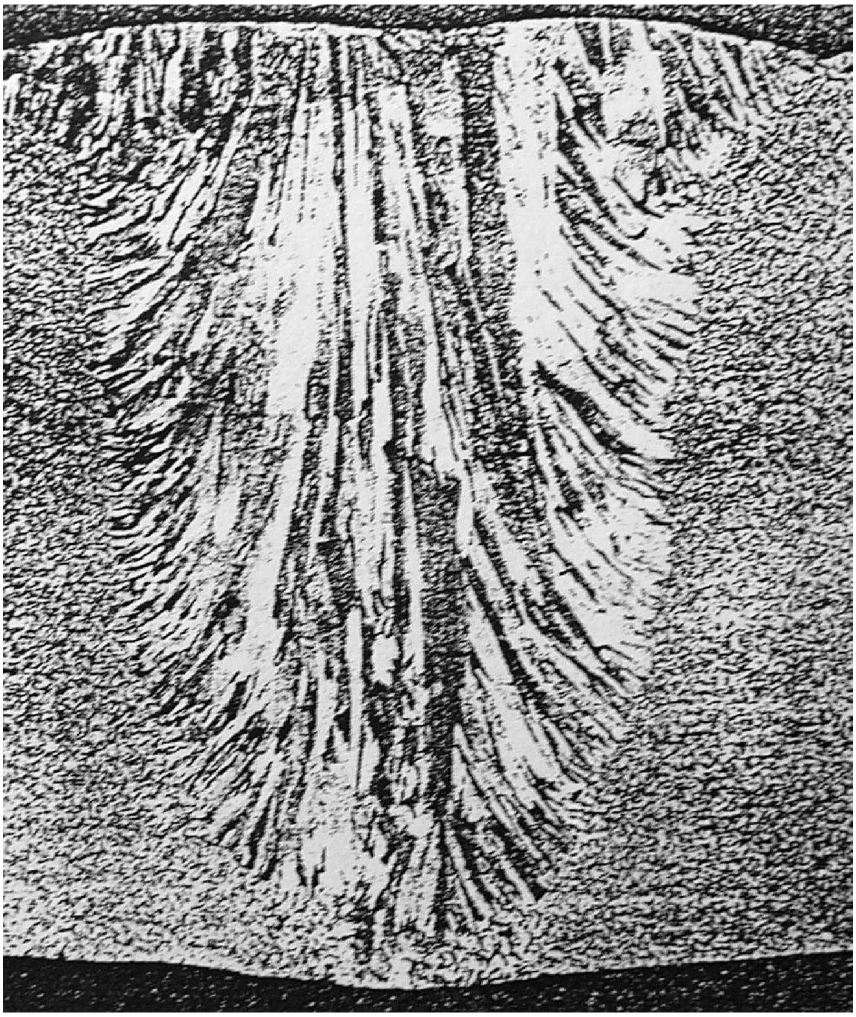


Figure 1 The grain direction adjacent to a weld fusion face is perpendicular to the fusion face (example of a Shielded Metal Arc weld)

A simple model can be derived in which the heat flow into the previous weld bead (H_B) and the heat flow into the previous layer of weld beads (H_L) are combined to give the average heat flow vector (H) (Figure 2). The direction of the heat flow (θ), which is given by:

$$tan\ (\theta) = H_B/H_L$$

then determines the grain angle.

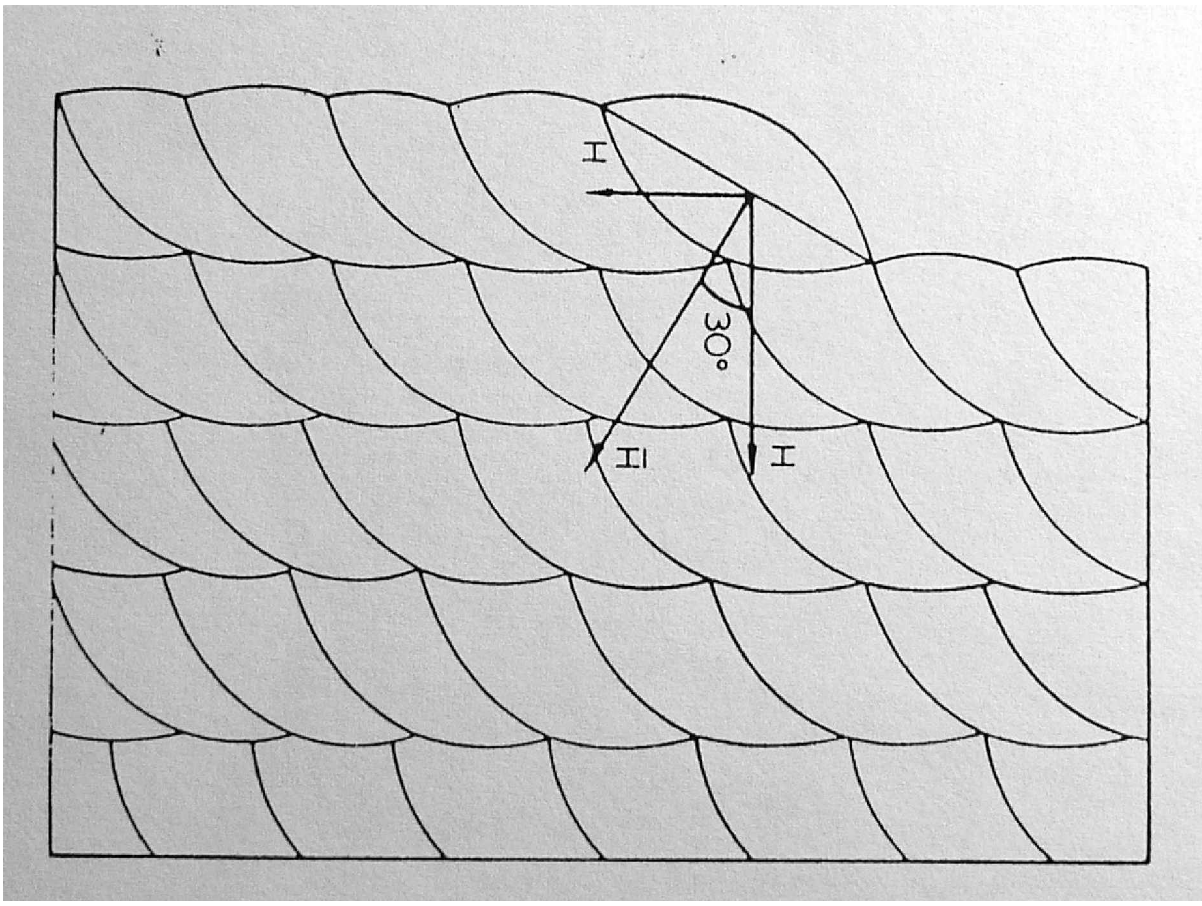


Figure 2 The heat flow into the previous layer of weld beads (H_L) are combined to give the average heat flow vector (H)

Welding Types

This section briefly describes the features of the most commonly used welding processes which affect ultrasonic wave propagation.

Shielded Metal Arc Welding (111-SMAW) generally forms relatively small weld beads, with highly ordered columnar grain structures (Figure 1).

Submerged Arc Welding (12-SAW) is used for high deposition rates and generally gives rise to large weld beads (Figure 3). Due to their large size, neighbouring weld beads have a significant effect on the heat flow direction, which results in fan shaped grains that are confined to a single weld bead. In cases where the heat input is low, the weld bead size is smaller and the grain structure is more like that of a 111 (SMAW) weld.

Gas Tungsten Arc Welding (141-GTAW) produces high quality welds with small weld beads. The resulting grain structure is highly ordered similar to that for 111 (SMAW) welds (Figure 4). 141 welding (GTAW) is a common process for fabricating narrow-gap welds (Figure 5).

Electroslag Welding (72) gives a structure similar to casting. The weld preparation is similar to narrow gap welding (Figure 6).

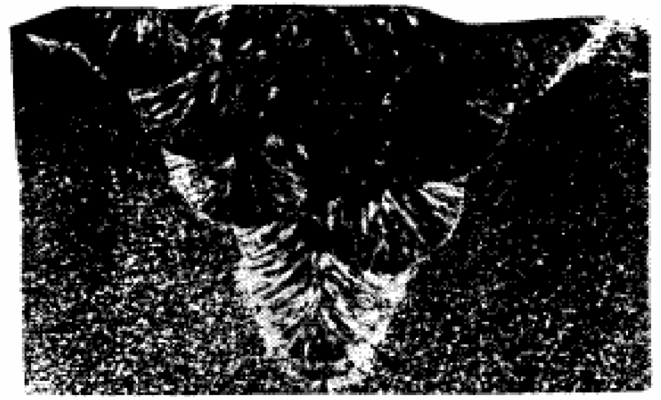


Figure 3 Submerged Arc Welding (12-SAW)

Figure 4 Gas Tungsten Arc Welding (141-GTAW)

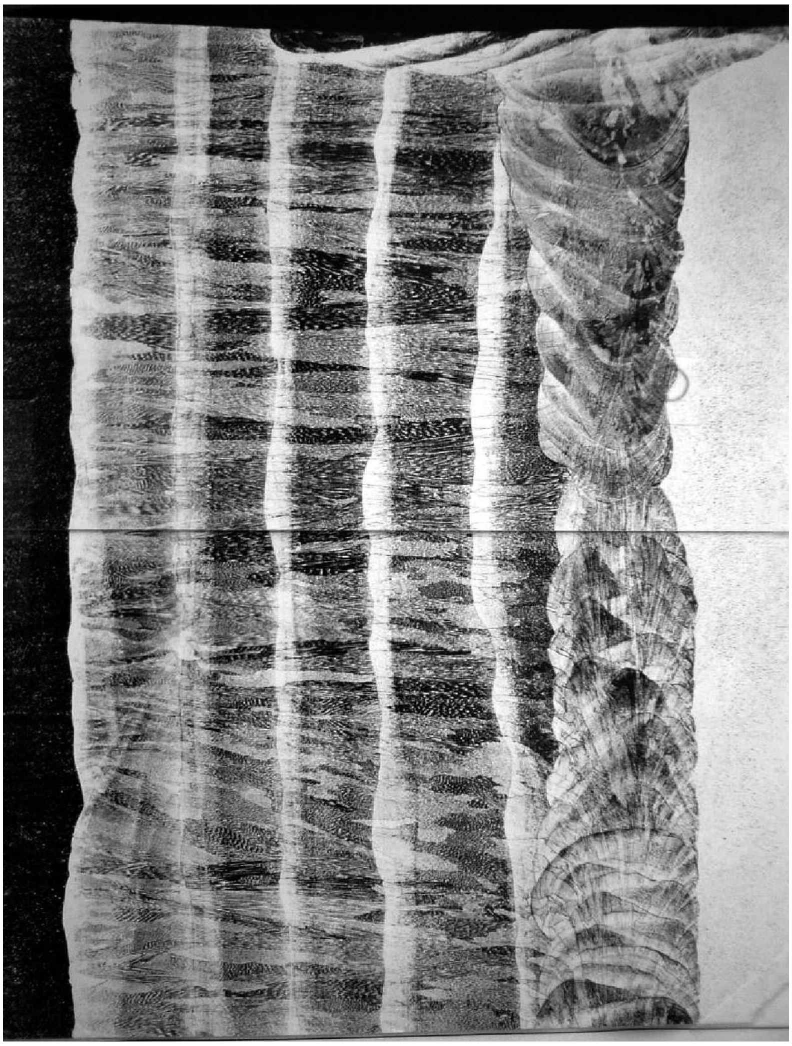


Figure 5 Narrow-gap weld (inconel weld between an inconel buttering and a wrought stainless steel part)

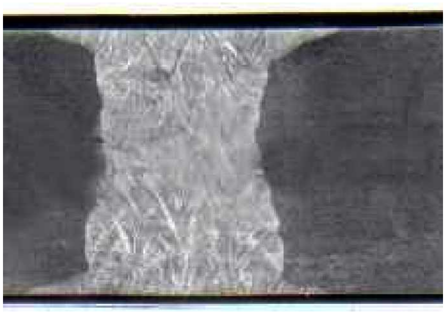


Figure 6 Electroslag weld (72)

Welding Position

The simple model described in section 0 can be used to understand how welding position affects the grain angle distribution.

When welding a pipe butt joint in a horizontal pipe run, the welding position varies around the circumference of the pipe as shown in Figure 7. At different locations around the pipe, there are different angles between the vertical direction (i.e. the direction in which gravity acts) and the heat-flow direction. As a result, the grain orientation relative to the pipe changes with location along the weld where different welding positions apply. The effect is illustrated in Figure 9 and Figure 10 which show transverse and longitudinal sections of a pipe butt weld for different positions. The macrograph in Figure 9 is for a section of weld close to the top of the pipe where the welding position is downhand. The macrograph in Figure 10 is for a section of weld on the flank of the pipe where the welding position is vertically up. The grain structure as seen in the transverse section of the Figure 9a and Figure 10a is similar for the two cases but the longitudinal section (Figure 9b and Figure 10b) reveals significant variation in the grain direction relative to the local throughwall direction. For the downhand position, the grains are close to the throughwall direction. In the vertically-up position, the grains are tilted by some 15° from the the throughwall direction. This tilt in the longitudinal section is known as the « layback angle ».

Note that downhand welds may also have a layback angle related to the rate of deposition of weld metal along the joint.

When welding a pipe butt joint in a vertical pipe run as shown in Figure 8, the welding position is “horizontal-vertical“ (ISO PB) at all points around the circumference of the pipe. For the downhand (ISO PA) and vertically-up (ISO PF) positions just considered, the pattern of the heat flow direction is symmetrical with respect to the plane of the weld centre line so that the resulting grain structure is also symmetrical with respect to the weld centre plane. For the horizontal-vertical position, the heat flow pattern is no longer symmetrical with respect to the weld centre resulting in the asymmetrical grain structure shown in the Figure 11.

The implications for ultrasonic inspection of these positional variations are discussed in Section 5.

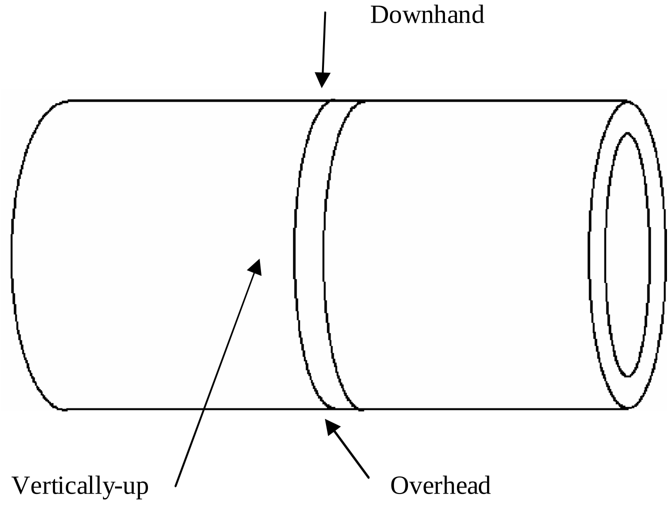


Figure 7 A pipe weld that has been welded positional will experience all welding positions from overhead, through vertically, to downhand and hence the layback will vary around the circumference of the weld

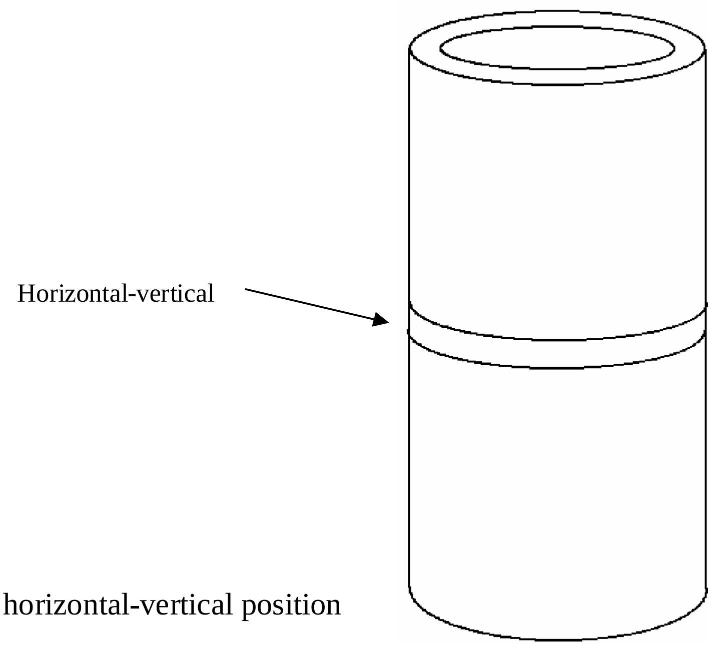
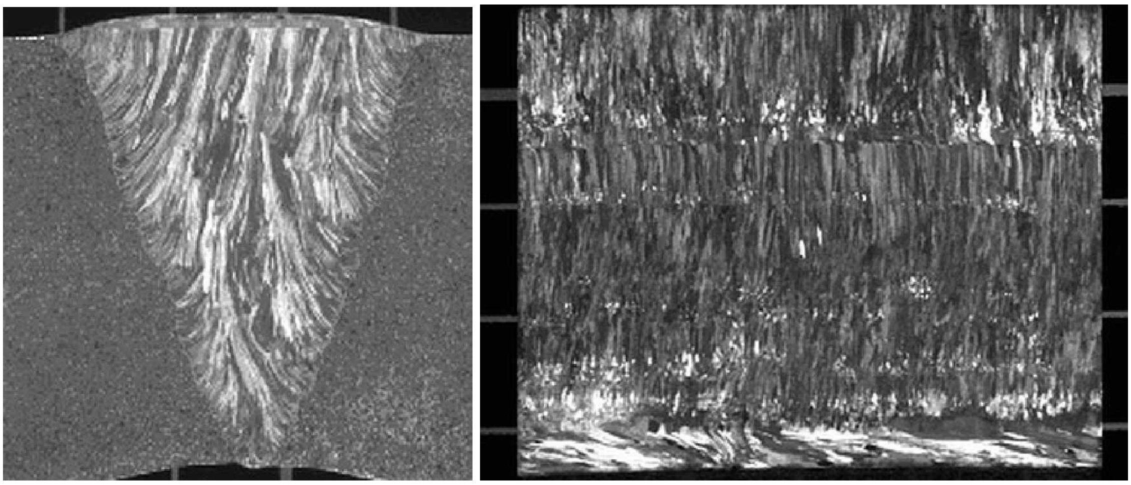
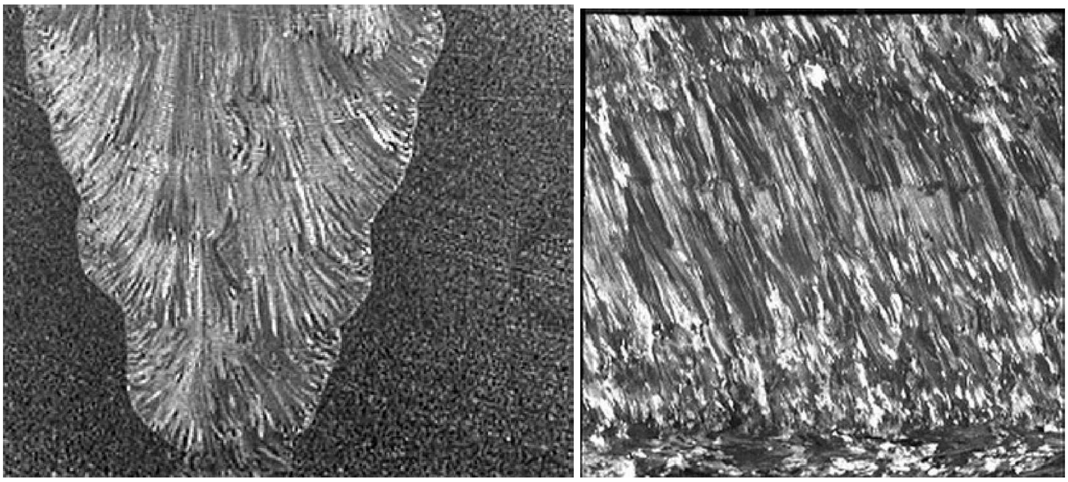


Figure 8 Welding in horizontal-vertical position



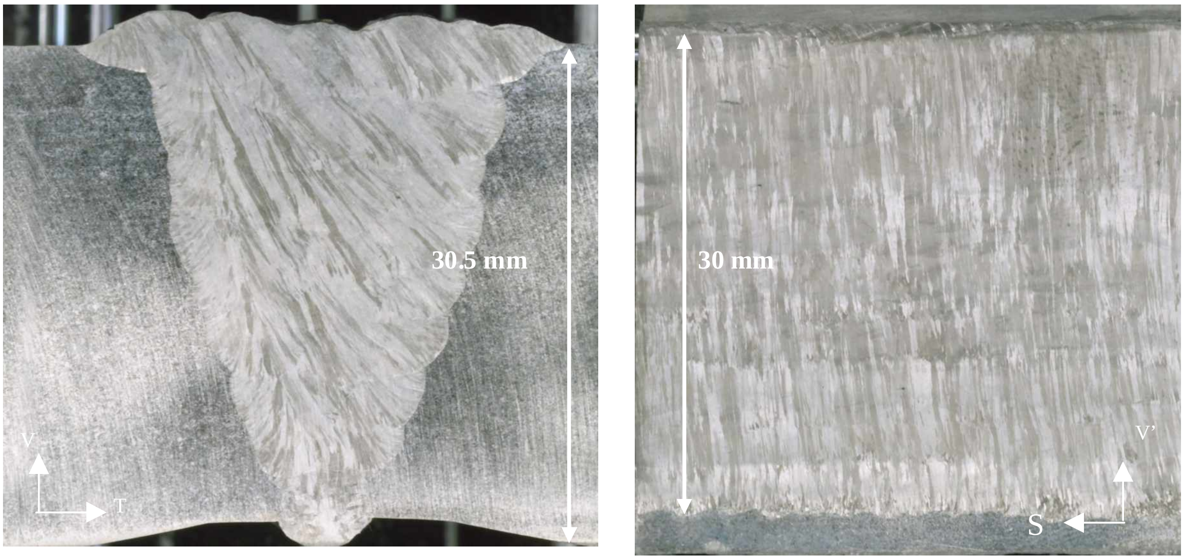
a b

Figure 9 Transverse (a) and longitudinal (b) sections of a weld fabricated in the downhand position.



a b

Figure 10 Transverse (a) and longitudinal (b) sections of a weld fabricated in the vertical-up position.



a b

Figure 11 Transverse and longitudinal sections of a horizontal-vertical weld

Weld Repairs

Weld repairs are an important factor in inspection design and capability. A repair will disrupt the expected grain structure resulting from the design weld procedure. The weld repair may also extend into the parent material thereby increasing the width of the weld over a local region. In some cases, the location and size of weld repairs will be documented but in general it must be assumed that such information is not available. The repair welding process and grain orientation may differ from that of the original weld.

During ultrasonic inspection, a weld repair is often appearing as a local region of different noise or attenuation. It may also be undetected, in which case the repair may have no detrimental effect on the inspection. The practical effects of weld repairs on ultrasonic inspection could be:

- a region of higher (or lower) noise generated by a weld repair could give rise to false calls. This effect may be made worse if the repair extends into the parent material where discrete reflections from the (unknown) fusion face are possible.

- potential masking of defect close to the repair.

- the actual inspection capability of a repaired area may differ from that predicted from the original modelling and test block trials.

Wherever possible the effect of weld repairs should be anticipated and techniques should be specified that minimise their effect.

Dissimilar Metal Welds

A dissimilar-metal weld consists of a ferrite steel piece joined to an austenitic steel piece by a fusion weld. It is also defined as transition weld or bimetallic weld.

Ultrasonic inspection of dissimilar metal welds is generally more complicated than a normal austenitic weld. This is due to the wider range of grain structures that may be encountered along the beam path and the larger volume of coarse grain weld metal that exists.

The main distinctive feature of a dissimilar metal weld (Figure 12) is buttering layers, which provide a gradual transition in material properties from the ferritic base to the weld volume. It is also common for the ferritic side to be clad with austenitic steel on the inner surface (and sometimes on the outer surface) to provide corrosion resistance.

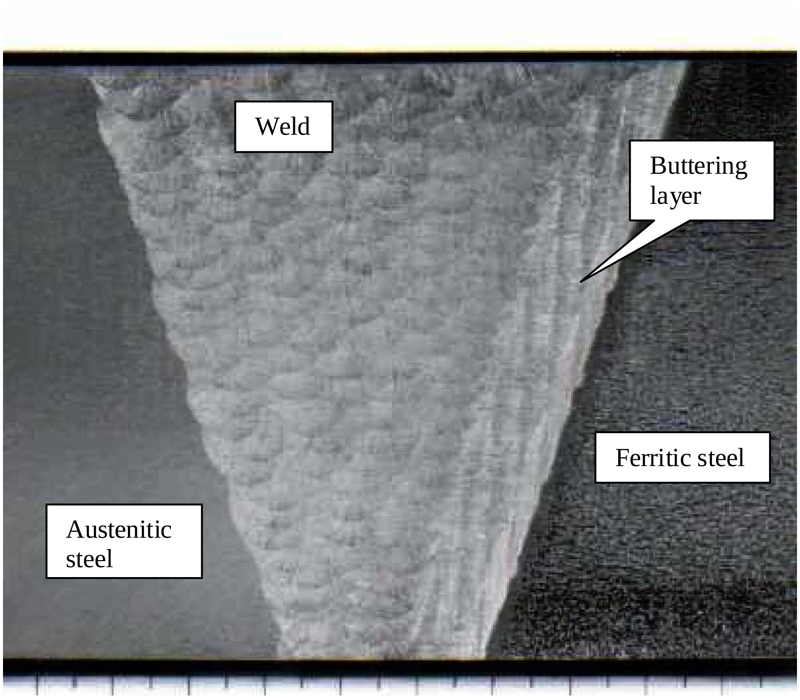


Figure 12 The main distinctive feature of a dissimilar metal weld

Welds in Duplex Stainless Steels

Duplex stainless steels are widely used in the petrochemical industry for their combination of mechanical properties and resistance to stress corrosion cracking (SCC). Duplex steels have good resistance to SCC, pitting and crevice attack and good mechanical properties.

The tendency for steels to form either an austenitic or ferritic structure is largely dependent on the ratio of alloying elements. The main alloying element in stainless steels is Chromium (Cr), which encourages the self-healing oxide film that gives stainless steels their characteristic resistance to corrosion. Chromium promotes the formation of ferrite. The other main alloying element is Nickel (Ni), which also gives resistance to corrosion. Nickel promotes the formation of austenite. (Other alloying elements, such as carbon, molybdenum, manganese, as well as the cooling rate, also play a vital role in phase formation). The Cr-Ni equivalent/ratio influences the extent to which an austenitic or ferritic structure is attained.

For duplex steels, a high Cr-Ni ratio is expected, typically 22 to 23%Cr, 8%Ni and 25%Cr, 4-8%Ni for super-duplex to keep 50/50 austenitic/ferritic ratio.

3 Defects

Manufacturing defects

Manufacturing defects can be summarised in the following tables.

Table 1 Casting manufacturing defects

Manufacturing process	Planar discontinuities		Volumetric discontinuities	
	Surface	Sub-surface	Surface	Sub-surface
Sand casting Investment casting Die casting Pressure die casting	Cracks, Hot tears, Inserts, Cold Shuts, Shrinkage	Cracks, Inserts, Cold Shuts, Shrinkage	Porosities Sink, Collapsed core, Gas cavities, Inclusions	Inclusions, Inserts, Collapsed core, Gas cavities, Shrinkage

Table 2 Manufacturing defects in wrought products

Manufacturing process	Planar discontinuities		Volumetric discontinuities	
	Surface	Sub-surface	Surface	Sub-surface
Hot rolling Cold rolling Extruding Drawing	Cracks, Pitting, Indentations and grooves, Scratches, Lamination (flat products), Piping (bars), Seams, Stringers	Cracks, Lamination, Piping, Inclusions (Stringers)	Rolled-in scale, Inclusions	Inclusions Piping (bars),

Table 3 Manufacturing defects in forgings

Manufacturing process	Planar discontinuities		Volumetric discontinuities	
	Surface	Sub-surface	Surface	Sub-surface
Drop forging Press forging Hand forging Hot and cold stamping	Cracks, Indentations and grooves, Scratches, Laps	Cracks, Laps, Inclusions	Embedded scale, Inclusions Burns	Inclusions Burst

Table 4 Welding manufacturing defects

Product form		Planar discontinuities		Volumetric discontinuities	
Welding	**Welding Process (ISO 4063)**	**Surface**	**Sub-surface**	**Surface**	**Sub-surface**
Plate in line butt Tee butt Cruciform Tubes & pipes circumferential butt linear butt nozzle node	MIG,(131) MAG (135), TIG (141) , MMA (111), SAW (121)	Cracks Lack of fusion Incomplete penetration Re-heat defect	Cracks Lack of fusion Incomplete penetration	Porosity Imperfect shape including undercut	Porosity Inclusions

Service Induced Defects and Degradation

Table 5 summarises different types of service induced defects. During inspection the crack opening displacement (COD) at the surface can vary from "very tight" (2-5µm). to "open" (>20µm).

Table 5 Summary of different types of service induced defects

Planar discontinuities		Volumetric discontinuities	
	Morphology		Morphology
Transgranular cracks,	Rough	Erosion,	Local thickness reduction
Intergranular cracks,	Rough, often branched	Corrosion	Local thickness reduction
Mechanical fatigue	Smooth	Impact,	Local thickness reduction
Thermal fatigue	Rough or smooth/forming a net	Wear damage	Local thickness reduction
Intergranular attack	Along the grain		

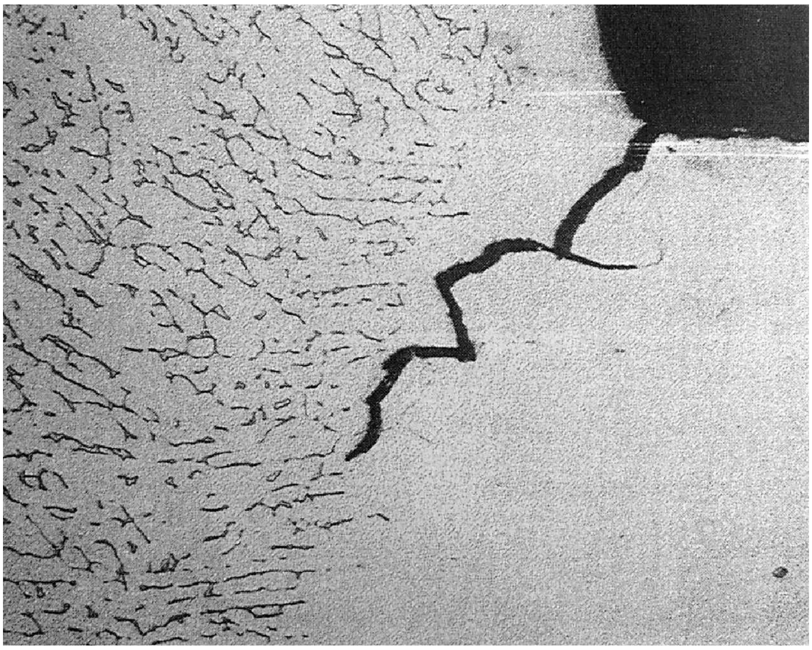


Figure 13 Mechanical fatigue crack (magnification 200X)

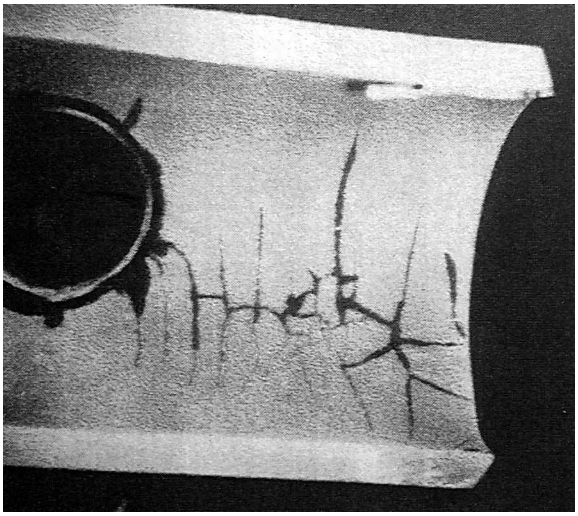


Figure 14 Thermal fatigue cracks (magnification 0,5X)

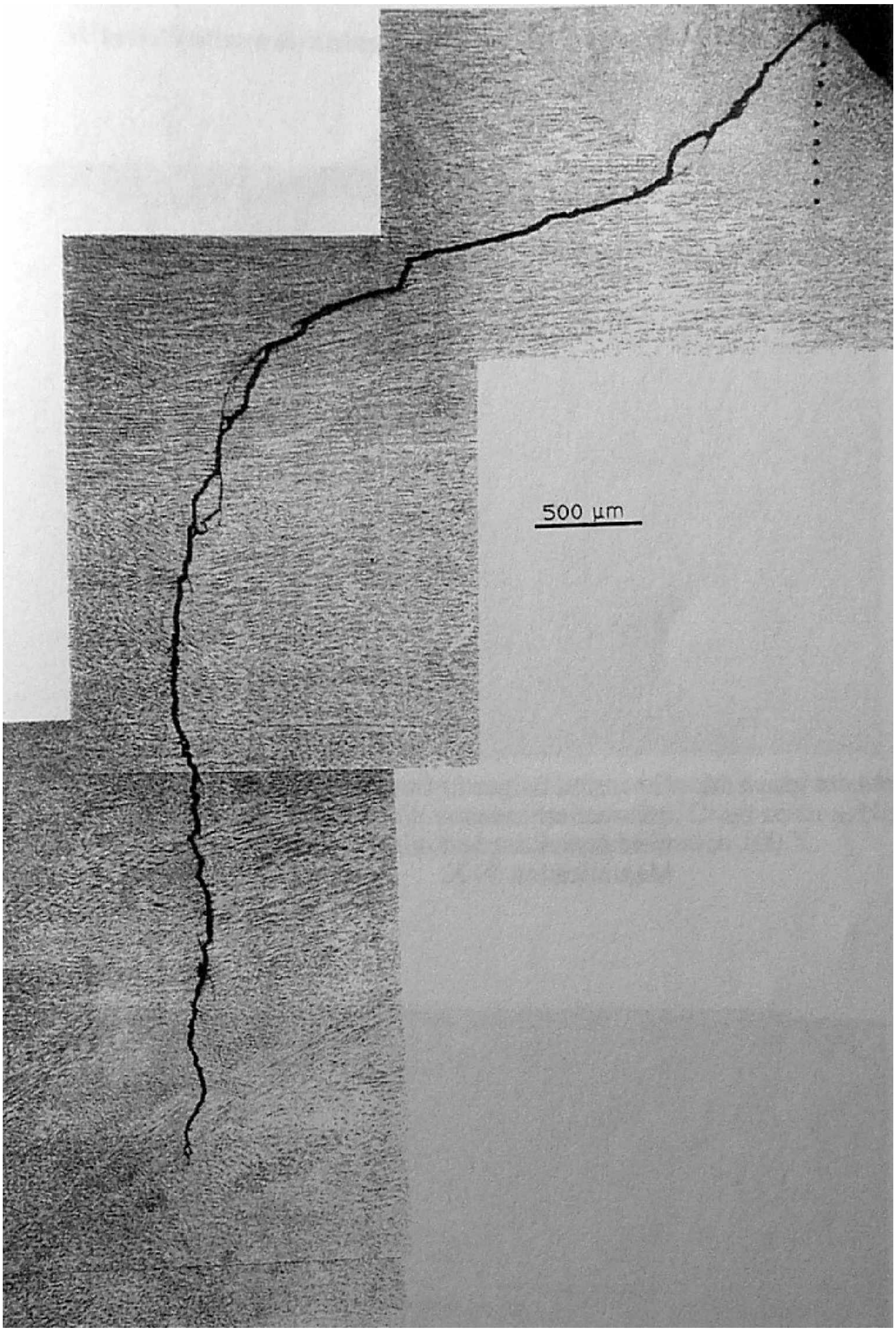


Figure 15 Thermal fatigue crack (magnification 30X)

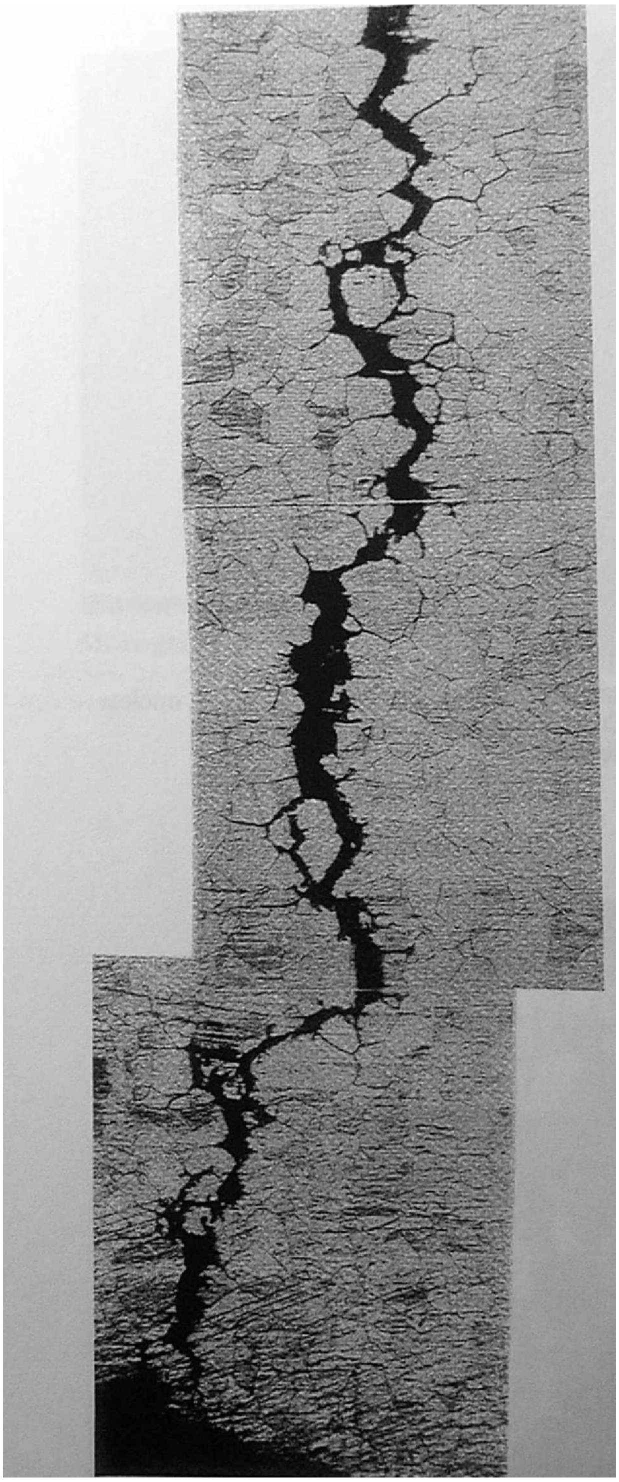


Figure 16 IGSCC (magnification 37,5X)

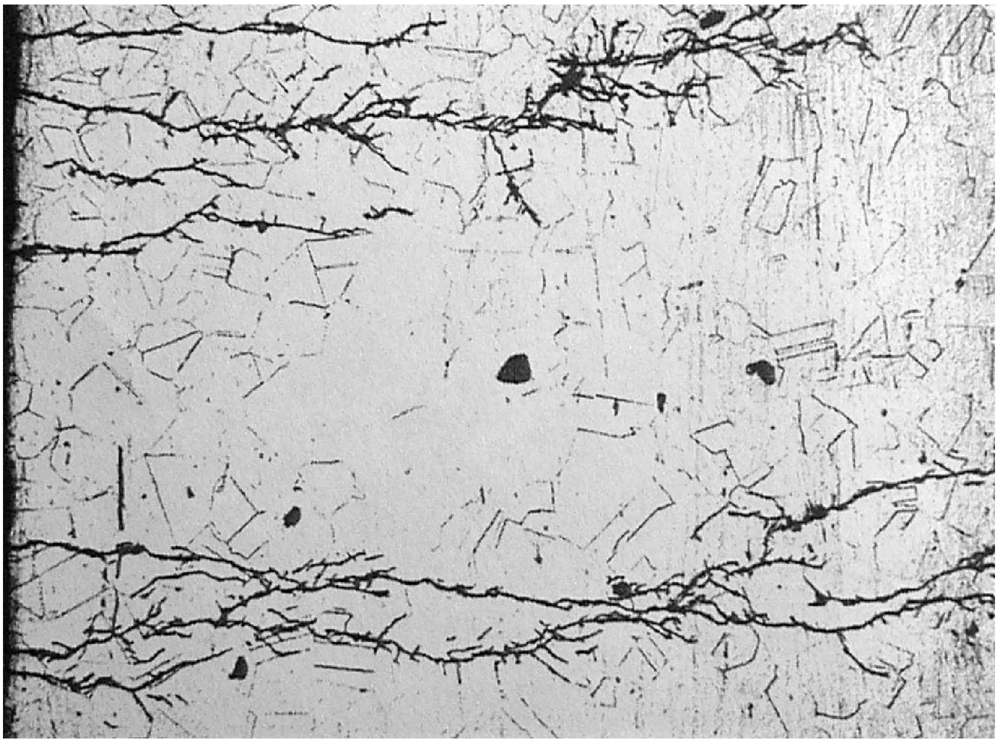


Figure 17 Transgranular crack (magnification 100X)

Mechanical fatigue cracks

Crack growth and initiation are due to external alternating service loads. Very often, there is some interaction between the external load effect and some residual internal stresses (from the welding or from the manufacturing stage).

Mechanical fatigue cracks are surface breaking, usually oriented perpendicular to the major stress direction and single. They are normally smooth, sharply tipped and unbranched.

Thermal Fatigue Cracks.

Similarly to mechanical fatigue cracks, thermal fatigue cracks initiation and growth are caused by alternating loads but from a thermal origin. Nevertheless, the resulting crack morphology can be different. The alternating thermal loads may cause a large number of cracks. The absence of a typical major stress direction makes that any orientation can be obtained.

Intergranular Stress Corrosion Cracking (IGSCC)

Intergranular stress corrosion cracking is caused by internal (residual) stresses and/or external loads combined with corrosion. This degradation can be found in very different materials like ferritic low alloy steels or austenitic stainless steel structures.

Compared with fatigue cracks, the IGSCC is usually more branched and the crack is not straight. The morphology of the crack tip is typically branched and very sharp.

Transgranular Stress Corrosion Cracking (TGSCC)

The propagation of this type of crack is through the grains. The morphology of the crack tip is typically branched and very sharp.

Intergranular Attack (IGA)

Intergranular attack is a metal degradation caused by an attack of the joints between the grains. The grain themselves are not (or just a little) affected by the attack.

IGA can be explained by a higher thermo dynamical instability and a different composition of the joints compared to the grains.

There is no typical crack orientation. The phenomenon is located in the heat-affected zone.

Corrosion

Corrosion is a surface degradation caused by a chemical and/or an electrochemical action. The long time effect is the diminution of the thickness.

Erosion

Erosion is a surface degradation caused by a high flux of fluid. The long time effect is the diminution of the thickness. Erosion is very often combined with corrosion.

4 PROPAGATION OF ULTRASOUND THROUGH AUSTENITIC WELDS

This section introduces some of the phenomena that occur when ultrasonic waves propagate through coarse grain anisotropic weld material. It aims to give a better understanding of these effects and how they might influence ultrasonic inspection.

Introductory Remarks

The presence of austenitic weld metal can seriously affect the ultrasonic inspection of a component because of:

- distorted wave propagation within the weld material.
- reflection of ultrasound at the fusion boundary between the parent material and the weld (appendix 1).

The reader will come across several phenomena which do not exist in "normal" (isotropic) materials and which are unfamiliar to most ultrasonic operators such as:

Anisotropy: An anisotropic material is one in which the properties of the material, e.g. ultrasonic sound velocity, vary with the direction in which they are measured.

Beam deviation: Beam deviation is said to occur when an ultrasonic beam propagates in a direction which is not perpendicular to the wave front. This phenomenon can cause unexpected changes in beam direction and shape. (The term "beam skewing" is also used and should not be confused with the squint or skew angle of twin crystal probes).

Scattering: The scattering of ultrasonic beams is not usually a problem when examining ferritic materials, except at high test frequencies, e.g. 10 MHz and above. Welds in austenitic materials have coarse macrostructures which cause significant scattering of ultrasonic beams at relatively low frequencies, e.g. 2 MHz. This can lead to very low signal-to-noise ratios for some ultrasonic examinations.

The extend to which the above phenomena affect ultrasonic testing depends on many factors such as

- beam direction relative to the columnar grains
- wave mode
- test frequency as mentioned in the "Scattering section"

Section 4.2 explains the physics of ultrasonic wave propagation in austenitic welds due to its macrostructure as simply as possible.

Physics of Wave Propagation in Austenitic Weld Material

Wave Mode and Polarisation

In isotropic materials two different wave modes can occur, namely compression waves and shear waves. The difference between the two is in the direction of particle motion or polarisation. It is parallel to the direction perpendicular to the wavefronts ("the wave normal direction") for compression waves and perpendicular to it for shear waves.

In principle the number of possible shear wave modes is infinite since the particle motion can have any direction perpendicular to the wave normal. In practice only two types of polarisation are used for ultrasonic inspection:

- particle motion is in the plane of incidence (Figure 19) for shear waves generated by conventional piezoelectric transducers. This is the vertically polarized shear (Sv) wave mode (the plane of polarization is in the vertical plane)
- particle motion is in the plane perpendicular to the plane of incidence (Figure 19). This is the horizontally polarized shear (Sh) wave mode (the plane of polarization is in the horizontal plane). Sh waves, which are usually generated by EMATs (appendix 5) may offer benefits for some practical applications.

Only three wave polarisations can exist in anisotropic material such as austenitic weld metal, namely one compression wave mode and two shear wave modes. The directions of particle motion are always mutually perpendicular but in general:

- they are not parallel to the wave normal direction for compression waves
- they are not perpendicular to the wave normal direction for shear waves.

This is discussed in more detail in appendix 2.

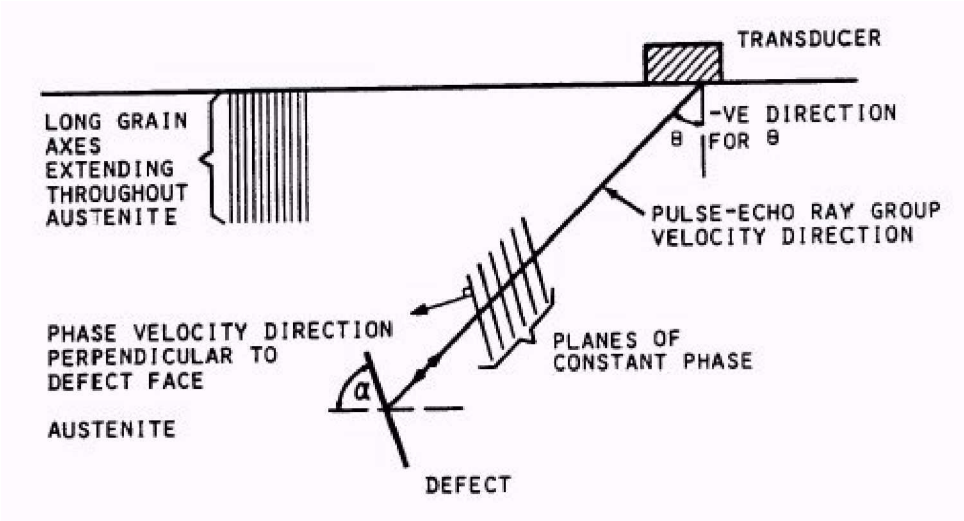


Figure 18 Visualization of the wave front normal and the direction of energy flux, i.e. "propagation direction" of an angle beam.

Unlike isotropic materials, the velocities of the two polarised shear waves are generally different for anisotropic materials.

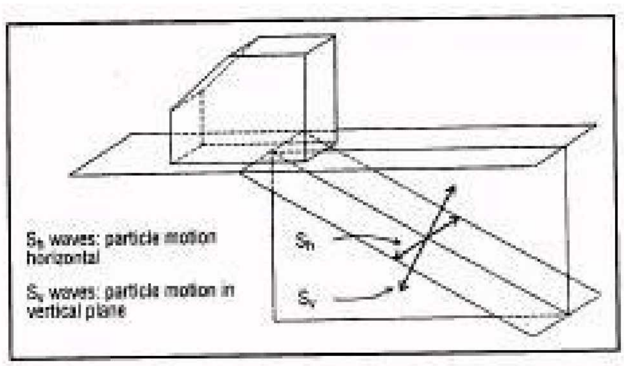


Figure 19 Particle motion is in the plane of incidence for shear waves generated by conventional piezoelectric transducers.

Velocity of Ultrasonic Waves in Austenitic Materials

The velocities of compression and shear waves in ferritic steel are different but independent of beam angle. Consequently, ferritic steel is said to be acoustically isotropic.

Figure 22 shows the propagation of compression waves in ferritic steel from a hypothetical point source. In three dimensions it will represent a spherical wave front.

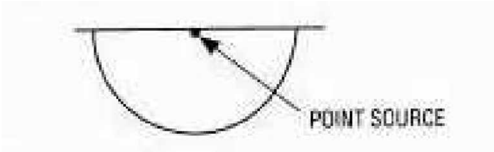


Figure 20 The propagation of compression waves in ferritic steel from a hypothetical point source. In three dimensions it will represent a spherical wave front.

shows the formation of a plane wave in ferritic steel using Huygens' principle for a large number of point sources across the width of an ultrasonic 0° probe. The wave front will propagate in a direction at right angles to the surface. Its velocity will not vary with direction. The velocity of a point of constant phase on the wave front in is called the phase velocity (Vp). The direction of Vp is perpendicular to the wavefront. The phase velocity surface is the three-dimensional surface obtained by plotting the size of the phase velocity in polar form.

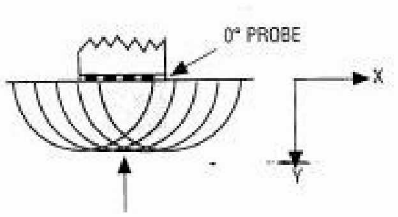


Figure 21 The formation of a plane wave in ferritic steel using Huygens' principle for a large number of point sources across the width of an ultrasonic 0° probe

The energy of the wave in ferritic steel will propagate in the same direction as the wave fronts and have the same velocity. So the energy or group velocity (Vg) of the wave equals Vp and the group velocity surface also has a spherical shape.

The phase velocity Vp of compression waves in austenitic weld metal is a function of the angle between the wave normal direction and the long axis of the columnar grains. In general, the group velocity Vg does not have the same direction and magnitude. So neither the wave fronts of a point source (or phase velocity surface), nor the group velocity surface will have a spherical shape.

To describe the effects that occur as ultrasound passes through austenitic weld material it is simplest to consider the case where the grains are all straight, the structure is homogeneous but still anisotropic as in the case of austenitic cladding. The phase velocity Vp in such material can be calculated from time-of-flight measurements. This can be performed on parallel-sided blocks machined from weld pads that have been fabricated to give a uniform grain structure.

Figure 24 shows two-dimensional sections of the phase velocity surfaces for all three wave modes in austenitic weld metal. In this figure the direction of phase velocity is given as the angle between the wave normal and the columnar grain direction.

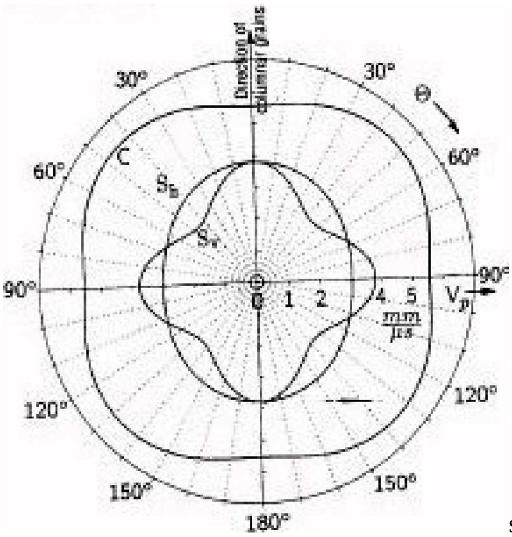


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Figure 22 Two-dimensional sections of the phase velocity surfaces for all three wave modes in austenitic weld metal. In this figure the direction of phase velocity is given as the angle between the wave normal and the columnar grain direction.

Figure 23 shows the group velocity Vg for compression waves in homogeneous weld metal (the group velocity for shear waves is more complex and is discussed in appendix 1).

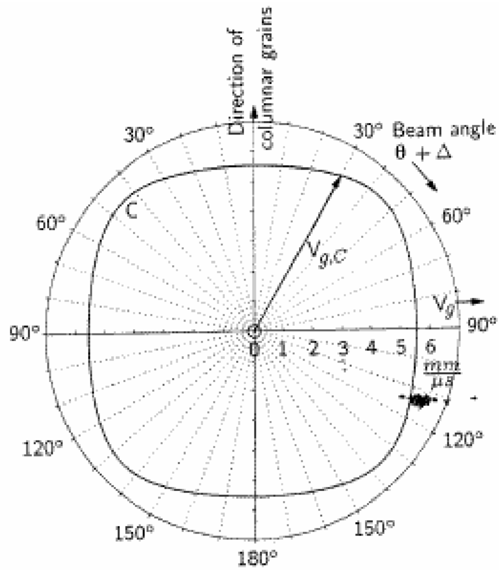


Figure 23 The group velocity Vg for compression waves in homogeneous weld metal

When using the Huygens' principle for construction of wave propagation in anisotropic materials the group velocity surface must be used. Each portion of the group velocity surface corresponds to the wave front for a plane wave with energy travelling in that direction.

Figure 24 illustrates this qualitatively for a point source of compression waves in homogeneous austenitic weld metal with tilted grains.

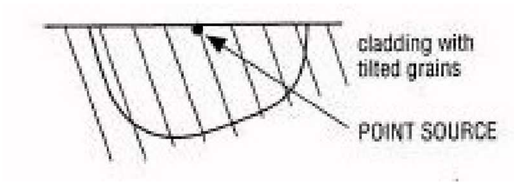


Figure 24 A point source of compression waves in homogeneous austenitic weld metal with tilted grains

Figure 25 shows a plane wave front generated by a 0° probe in the same material constructed by Huygens' principle.

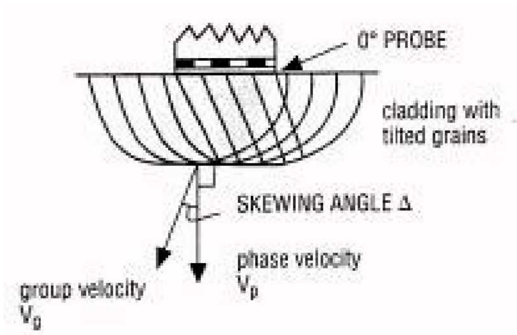


Figure 25 A plane wave front generated by a 0° probe in the same material constructed by Huygens' principle

The similarities between , for ferritic materials, and , for anisotropic material are:

- the wave front is parallel with the surface.
- the directions of the phase velocity Vp are the same, namely perpendicular to the wave front.

The differences between these two figures are:

- the magnitudes of phase velocities Vp and group velocities Vg will be different.
- in the anisotropic case obviously the wave's energy flow is travelling at angle Δ to the phase velocity Vp with group velocity Vg. Both velocities are related by:

$$\cos\Delta = Vp/Vg$$

For isotropic materials Vp and Vg are identical. The main reason why ultrasonic beams travel in unexpected directions in anisotropic materials is because Vp and Vg are, in general, not equal.

Beam Deviation Effects and Focusing/Defocusing Effects.

In the following discussion it is assumed that the grain structure is homogeneous and that the grain direction is in the same plane as the sound propagation.
The phase velocity surface for Sv waves is less circular than for compression and Sh waves and consequently Sv waves are most severely affected by material anisotropy. Another way of displaying this is by plotting the beam deviation angle as a function of the angle between the wave normal and the columnar grain direction as shown Figure 26. This shows that for compression waves the beam deviation angle Δ is zero for a wave normal to grain angle of 48º. The gradient of the curve at this angle results in a focusing effect producing narrower beam widths than would be otherwise obtained in ferritic steel. Conversely, when the wave normal to grain angle is 0º and 90º, the sign of the gradient changes such that compression waves are defocused. This results in wide beam widths and poor test sensitivities.

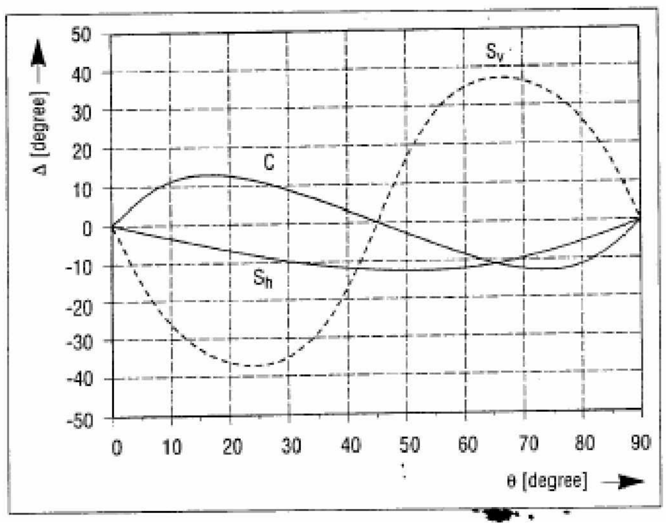


Figure 26 Computed beam deviation Δ versus the angle θ between the direction of the phase velocity and the long axis of the columnar grains.

The focusing/defocusing effect of Sv waves is in the opposite sense than for compression waves. The beam deviation angle is zero for wave normal to grain angle of 45º. The gradient of the curve at this point causes the beam to defocus whereas focusing occurs at wave normal to grain angle of 0º and 90º where the beam deviation angle is also zero. It should be remembered that Sv beam deviation is more severe than for either compression or Sh waves.

Snell's Law and Slowness Surface

Snell's law is widely used in ultrasonic inspection to calculate the beam angle of refracted or mode converted beams. The equation can be applied to isotropic materials with few complications.

$$\sin(\theta_1)/V_1 = \sin(\theta_2)/V_2$$

It is valid for anisotropic materials, if the phase velocities, which are dependent on propagation direction, are taken into consideration.

The appendix 3 shows how to apply Snell's law to anisotropic materials using the concept of the slowness surface.

Simulation

The effects of grain structure and grain orientation on beam propagation can be illustrated by mathematical modelling. Figure 27a shows a typical austenitic weld structure and Figure 27b shows an example of how that structure can be modelled to enable ultrasonic simulation. Figure 28 shows the simulation results for different angles and wave modes.

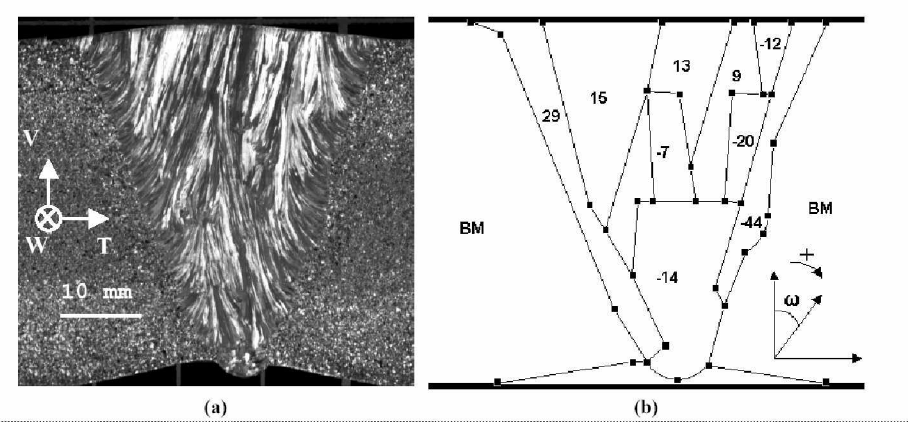


Figure 27 Macrograph of an austenitic weld and representation of the same weld showing different homogeneous domains.

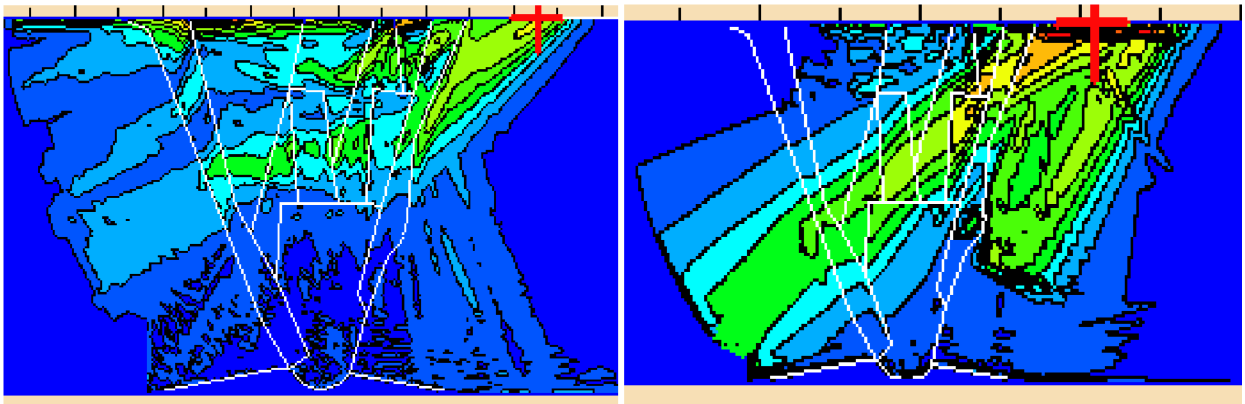


Figure 28 Calculated beam path for a 2,25 MHz 45° shear wave probe (left) and 2,25 MHz 60° compression wave probe (right).

Grain Boundary Scattering

Polycrystalline materials, like austenitic weld, attenuate ultrasound by grain boundary scattering. This produces a high level of noise (“grass”) as the scattered ultrasound returns to the probe. Grain boundary scattering is directionally dependent and different for each wave mode. It arises because neighbouring grains will have different crystallographic orientations (Figure 29). A sound beam crossing the boundary between grains will undergo a change in phase velocity. This change in velocity will result in a change in acoustic impedance between the grains. This produces a partial reflection at the boundary.

The difference in acoustic impedance between the parent and weld material generates a reflection. This varies with wave mode and angle of incidence. In particular the corner made by the fusion face and the free surface (at either the bottom or top of the weld) can give rise to quite strong reflections. The reflected energy when generates additional noise which in some cases can be quite strong.

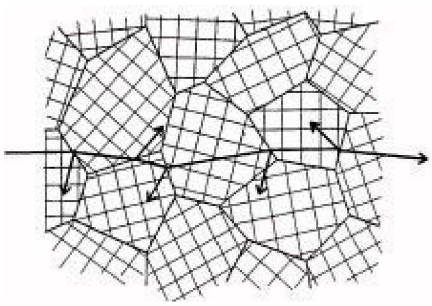


Figure 29 Grain boundary scattering is directionally dependent and different for each wave mode. It arises because neighbouring grains will have different crystallographic orientations

5 FACTORS AFFECTING INSPECTION CAPABILITY

Introduction

This section describes several factors affecting the inspection capability. Each factor and its effect are described separately but the overall capability in any particular case will depend on a combination of these factors.

Wherever possible austenitic welds should be fabricated in such a manner to provide the best inspection capability, It is however, recognised that this is not always possible or that the weld may have been fabricated before ultrasonic inspection was required.

Inspection development should take into account the possible extremes that may be encountered for a particular component by:

- collecting as much knowledge about the weld as is available
- using appropriate beam angles, frequencies, etc.
- designing suitable test samples for development and demonstrating capability

Access

The material surfaces to be used for the scanning must allow free movement of the probe(s) and provide satisfactory condition for the transmission of the ultrasonic waves. Therefore, the surface roughness should generally not exceed 6.3-12.5μm and the waviness should not exceed +/- 0.5mm over any area of 50mm * 50mm, otherwise, disturbance of the ultrasonic beam could reduce the sensitivity and result in errors in defect location.

Inspection capability will be significantly affected by the access available.

Where there is access to only one surface of the weld, any weld reinforcement must be removed if the whole volume is to be examined, as the “skip techniques”, used with shear waves on ferritic steel, are ineffective with compression waves, commonly used when examining austenitic welds. Where the weld reinforcement cannot be removed, the inspected volume will be limited. Furthermore, on each side of the weld and over a length depending on the technique to be applied, the surface should be free from weld spatter, loose scale, machining and grinding particles, dirt, paint or other foreign matter. It may be necessary to clean and smooth the surface with a flexible wheel sander. However, any surface preparation has to be performed in agreement with applicable requirements.

Parent Material

To allow adequate penetration of ultrasonic waves into the weld, the parent material should be transparent to ultrasound. Often, rolled plate and forged pieces are transparent but this needs to be verified (Appendix 6) since attenuation may be significant and subject to local variation. If localised variable attenuation is observed along the examination zone, the value must be taken into account to correct the sensitivity of the weld examination.

Austenitic castings are generally hard to inspect because of the extremely coarse grain structure. Some properties of the parent material are discussed in section2.1.

After adequate penetration is demonstrated, all zones through which the beams pass should be checked for defects that could obscure examination of the weld region. Specifications to examine parent materials are generally less stringent than for weld metal. However, in this case, the material adjacent to the weld should be examined at a sensitivity equal to that used for the weld examination.

Welding

Weld Volume

Since the coarse grain structure of austenitic welds both attenuates and scatters ultrasound, the signal detected at the probe will depend upon the path length of the ultrasonic beam in the weld material. From this point of view, a complete volumetric inspection of a wide weld will be more difficult than for one that is narrow (Figure 30). However, other factors are to be considered like attenuation, scattering and unfavourable defect orientation.

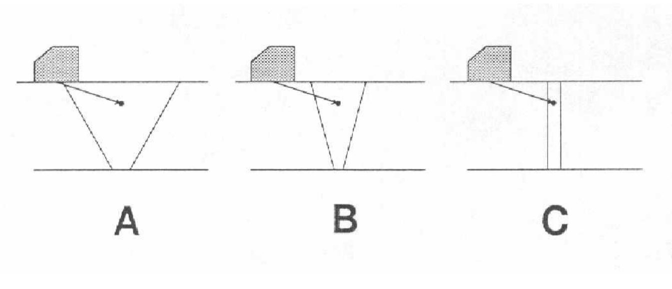


Figure 30 A complete volumetric inspection of a wide weld should be more difficult than for a narrow weld, if other parameters are equal.

Welding Position

The influence of the welding position on inspection capability can be observed from the following example. This considers the inspection of a weld in which the grain macrostructure is asymmetric about the weld centreline (Figure 31). The example shown is for an inspection using 60º angle compression wave probes from both sides of the weld. For Case A, the ultrasonic beam makes a relatively small angle with the grain angle for most of the path length causing the beam to diverge (see section 4). Conversely the angle between the beam and the grains for Case B is well away from 0º and 90º and therefore much more favourable for ultrasonic inspection than Case A. The signal to noise ratio for the side drilled holes would be significantly poorer for Case A than for Case B.

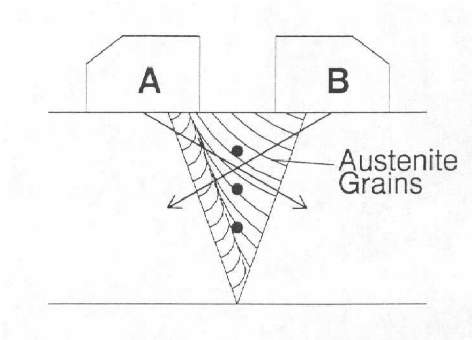


Figure 31 An example of a weld in which the grain macrostructure is asymmetric about the weld centreline.

As also shown in Section 2.2.3, the variation in welding position around a pipe butt weld in a horizontal pipe run leads to the existence of a significant “layback” angle in the longitudinal section (see Figure 10 and **Erreur ! Source du renvoi introuvable.**) where the welding position is vertically up. This can affect the detection and sizing capability for both longitudinal and transverse defects. Beams directed across the weld to detect or size longitudinal defects may be deviated out of the plane of incidence (i.e. the plane normal to the weld centre line) so that detection capability may be reduced and the accuracy of positioning features of any defect detected may be affected. Beams directed in opposing directions along the weld to detect transverse defects will have different directions relative to the grain axis direction so that detection capability may be different in the two directions.

A pipe weld that has been welded positional (Figure 7 and Figure 8) will experience all welding positions from overhead, through vertical, to downhand and hence the layback will vary around the circumference of the weld. In such cases the inspection may require a range of probes to provide adequate inspection capability for different circumferential sectors.

Weld Interfaces

Interfaces between weld and parent materials generate a step change in acoustic properties and consequently significant reflection and refraction of ultrasound may occur at such boundaries. The reflection/transmission properties will depend upon the relative acoustic properties of the weld and parent material and the angle of incidence of the ultrasound.

If the heat input during welding is high, then this will generate a cusped appearance at the weld interface (Figure 32 left). The reflection/transmission properties of the two cases will be different. In the high input case higher noise and localised discrete reflections that have a defect like appearance may arise. The lower heat input case is expected to give rise to reflections that are more uniform in appearance and are therefore easier to identify as spurious geometric indications.

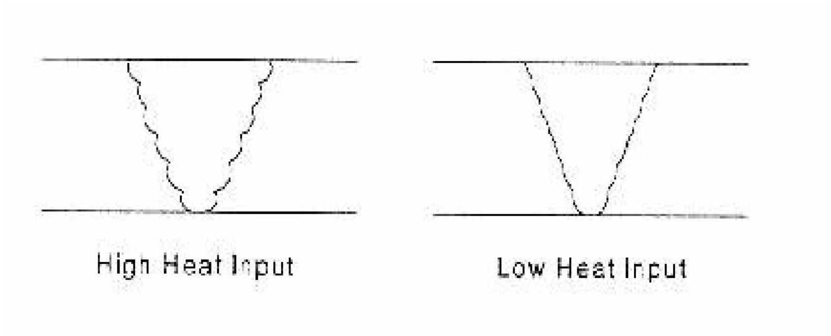


Figure 32 Appearance of the weld at the interface (see Figure 9 and Figure 10)

As shown in section 2, welds fabricated using the submerged arc process have a high heat input resulting in large bead sizes which generate fan-shaped grain structures within each weld bead. This is in contrast to the long continuous grains that traverse several beads characteristic of lower heat input MMA or TIG welds. It should be noted that large weld beads and fan-shaped grain structures can be generated by high heat input MMA and other processes. Fan-shaped grain structures tend to cause higher ultrasonic attenuation and noise levels and therefore may be more difficult to inspect.

Where a beam of compression waves strikes the interface between the weld and the parent material at a high angle of incidence (>~70°) there is a possibility of the beam being "totally reflected" by the interface. This is because of the action of Snell's law which can cause the refracted angle of the wavefronts on the far side of the interface to approach 90° as the angle of incidence increases. This can happen when the grain orientation is such that the phase velocity for high refraction angles is significantly higher on the far side of the interface. In practice the effect is likely to occur when the weld preparation has a large included angle and when a beam of relatively low angle (say 45° or less) is incident from the adjacent forging. Total reflection is most evident when the angle of the interface with respect to the throughwall direction is close to half the beam angle (for conventional butt weld geometry). The totally reflected beam is then reflected down to meet the backwall at right angles from where it reflects back up and is again totally reflected back to the probe. The result is a geometric echo. It is important to realise that the presence of a strong echo of this type shows that the beam concerned is not penetrating the weld and is therefore not contributing effectively to its inspection. The risk of failing to inspect part of the weld for this reason is much reduced if scanning can be carried out from both outside and outside surfaces (though this is often not possible).

Weld Repairs

Weld repairs can affect ultrasonic propagation in several ways:

- a weld repair that penetrates beyond the original fusion face will increase the weld width and consequently beam paths in coarse grain weld metal will increase

- a local disturbance of the grain structure within the weld volume will occur which often generates higher ultrasonic scatter

- the weld material and/or the welding process used in the repair may be different from that used in the original weld and the resulting acoustic mismatch may give rise to discrete ultrasonic reflections and/or scatter

Since weld repairs usually have a limited extent along the weld length the different ultrasonic properties of weld repaired regions will produce localised effects such as regions of high noise or discrete signals. Furthermore, the predicted inspection capability derived from the original models and/or test block trials will generally be different from that for a weld repaired region.

Dissimilar Metal Welds

Dissimilar metal welds exhibit many of the above features that make inspection difficult.

Figure 33 shows the typical features that make dissimilar metal welds difficult to inspect:

- a ferrite/austenitic boundary possessing a higher acoustic mismatch than conventional austenitic welds
- cladding on the bore of the ferrite side of the weld
- a large volume of weld metal due to the presence of buttering
- additional interfaces due to the cladding and buttering layers

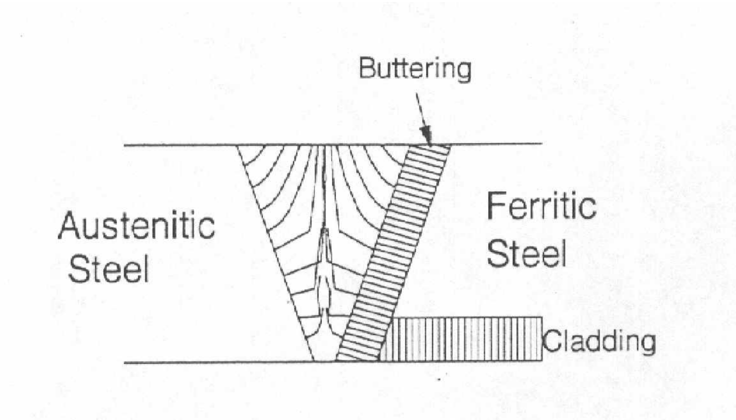


Figure 33 A typical configuration for a dissimilar-metal weld (see Figure 12)

6 ULTRASONIC TECHNIQUES

Overview of techniques for detection

The techniques to be used depend on the objectives of the inspection. The location and types of defects being sought is of primary importance.

Table 6 considers some of the more common inspection requirements and provides general guidance on the techniques that could be used.

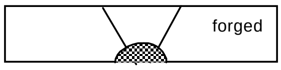
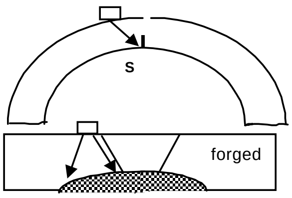
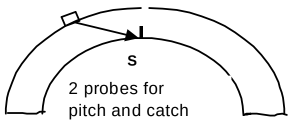
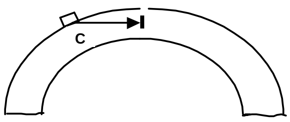
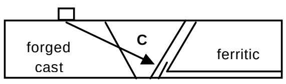
It must be emphasised that the suggested techniques are those which can be applied under ideal conditions (e.g. scanning surface, geometry, weld crown). In practice, the specific technique must be chosen taking into account all aspects of the inspection.

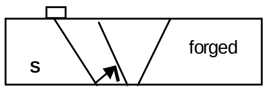
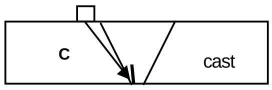
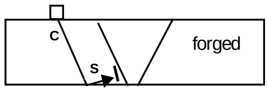
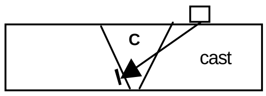
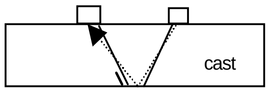
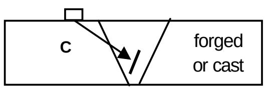
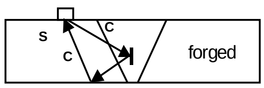
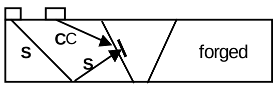
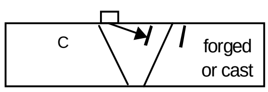
For austenitic inspection, there are many more factors, which influence inspection capability than for ferritic inspection (see section 5). Because of the reduced capability compared with ferritic, sometimes more than one of the suggested techniques must be applied.

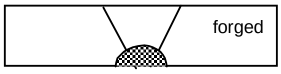
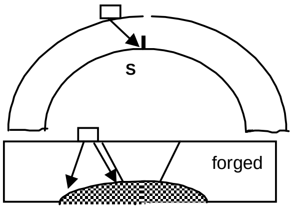
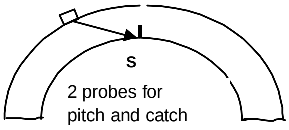
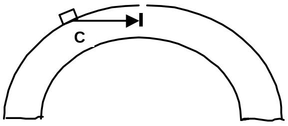
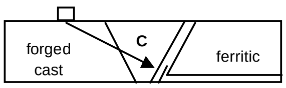
This table gives examples of inspection techniques from the outer surface. Where practicable, scanning from the inner surface can provide similar or additional information. The choice of the techniques, frequency and angles are based on the same principles.

Nearly all contact techniques can be performed in immersion with focused probes.

Table 6 Some of the more common inspection requirements and general guidance on the inspection techniques that could be used

Application	Configuration	Probes	Remark **Austenitic and Bimetalic Welds**
for surface cracks ⊥ er to the weld	 	shear vertical wave (SV) angle suitable for corner reflection shear horizontal wave (SH) for corner and specular reflection	*beam penetrating forging only *beam penetrating weld frequency depends on range
		comp. wave specular reflection	*probe angle selected to obtain specular rerflection
embedded cracks ⊥ er to the weld axis		compression wave (C) angle close to specular reflection	*beam penetrating weld *frequency depends on range
			Bimetalic Welds
inner surface breaking cracks parallel to weld axis		comp.wave (C),TRL probes, low frequency angle depend on thickness and fusion face angle	*both sides inspected, (C) penetrates the weld *(S) 1MHz from forged side can be helpful

Application	*Configuration*	*Probes*	*Remark* **Austenitic and Bimetalic welds**
inner surface breaking cracks parallel to weld axis angle of tilt between 0° and fusion face rough and smooth		45° - 70° compression wave (C) and or shear wave (S) f ~ 2MHz, single or twin crystall	*one side inspected, (S) does not penetrate the weld
		45° comp. wave (C), f ≤ 1MHz twin crystall (TRL)	*capability depends with thickness *both sides inspected, (C) penetrates the weld
		70° compression wave (C) or creeping wave, mode conversion 32° shear wave (S) and compression wave	*one side inspected, (S) does not penetrate the weld
		angled compression wave f ≤ 1 MHz, single or twin crystal	*probe angle selected according to expected defect angle of tilt
		angled compression wave in pitch and catch or TOFD configuration, f ≤ 1 MHz	*mainly a detection technique *development and optimisation recommended
Embedded cracks parallel to the weld axis rough and smooth		45° - 70° comp. wave (C), TRL f ~ 2-4 MHz forging f ≤ 1MHz casting	*angle or frequency depends on inspection depth *both sides inspected, (C) penetrates the weld
		angle compression wave using self tandem for depth of 2/3 thickness	*special dedicated probe using mode conversion (CCS) *both sides inspected, (C) penetrates the weld
			*one side inspected, (S) does not penetrate the weld
near surface breaking cracks parallel of the weld axis		70° compression wave (C) and creeping wave	f ≤ 1MHz if casting material is penetrated see also lack of fusion inspection from both sides

Application	Configuration	Probes	Remark **Austenitic and Bimetalic Welds**
for surface cracks ⊥ er to the weld			
		shear vertical wave (SV) angle suitable for corner reflection shear horizontal wave (SH) for corner and specular reflection	*beam penetrating forging only *beam penetrating weld frequency depends on range
		comp. wave specular reflection	*probe angle selected to obtain specular rerflection
embedded cracks ⊥ er to the weld axis		compression wave (C) angle close to specular reflection	*beam penetrating weld *frequency depends on range
			Bimetallic Welds
inner surface breaking cracks parallel to weld axis		comp.wave (C),TRL probes, low frequency angle depend on thickness and fusion face angle	*both sides inspected, (C) penetrates the weld *(S) 1MHz from forged side can be helpful

Equipment

The inspection can be performed manually or by using mechanised equipment. The choice depends on different factors such as: economical aspects, working environment, scope of the examination etc.

For manual inspection, conventional flaw detectors used for ferritic weld inspection are usually satisfactory for austenitic inspection. It is necessary to have appropriate matching of the ultrasonic equipment. Cable length and matching devices should be specified in the procedure.

The transmitting pulse and the amplifier characteristics can influence the inspection capability (signal to noise ratio). The amplifier response at low frequencies, its linearity and its bandwidth can be especially important.

Due to the fact that attenuation is high in austenitic material and is strongly dependent on ultrasound frequency, it is particularly important to control the frequency and bandwidth characteristics of the ultrasonic equipment.

Probes

Various possibilities exist for the selection of probe types for a particular examination of austenitic material. Particular attention must be paid to the damping of the probes. In many cases, highly damped probes give better results. Probe manufacturers provide guidance and characteristics of their probes.

Shear Wave Probes

The general properties of conventional shear wave probes (vertical polarised) are well understood and are not described here. These probes can have one or two crystals. As vertically polarised shear waves, in general, do not penetrate the weld material these probes are mainly used for the inspection of the parent material in front of the weld. The special case of horizontal polarised shear waves is discussed in section 6.3.3.5.

Although angled compression waves are necessary for examination of the weld volume, these are significantly less effective than shear waves in detecting surface breaking defects at the backwall. Given that austenitic welds are often susceptible to such defects in the HAZ (heat affected zone) it may be advisable to apply both compression and shear wave techniques. This approach requires access at both sides of the weld if both HAZs are to be covered.

Compression Wave Probes

A wide range of compression waves probes is used for the examination of austenitic structures because of the acoustic properties of these structures.

An important point to note is that angled compression wave probes also generate an associated shear wave beam at approximately one half of the beam angle of the compression wave. The presence of this additional beam, which can have an intensity comparable to that of the compression wave beam, should always be considered because it can cause spurious echoes and consequently give rise to misinterpretation of the results (Figure 34).

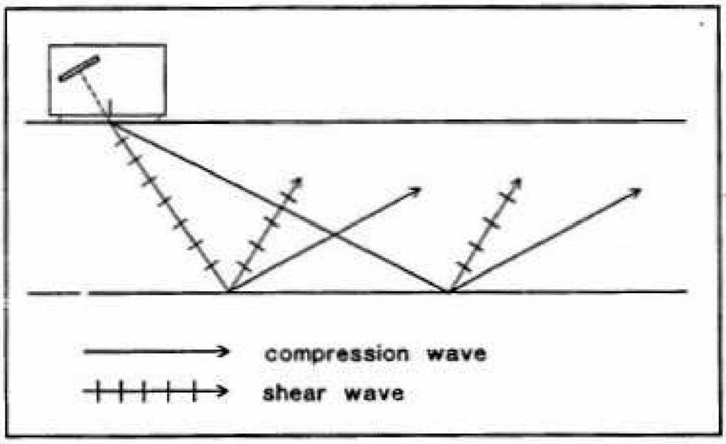


Figure 34 60° compression angle beam probe with shear wave part and mode conversion

Although the additional shear wave beam can cause confusion during the examination (because any indication could be located by either beam), careful consideration of range, angle and probe position relative to the weld often helps to decide which alternative is most likely. The echodynamic of the signal is also a useful distinguishing characteristic since the echodynamic of an indication arising from the compression wave is generally much wider that for the shear wave beam, because the compression wave has a larger beam width (Figure 35).

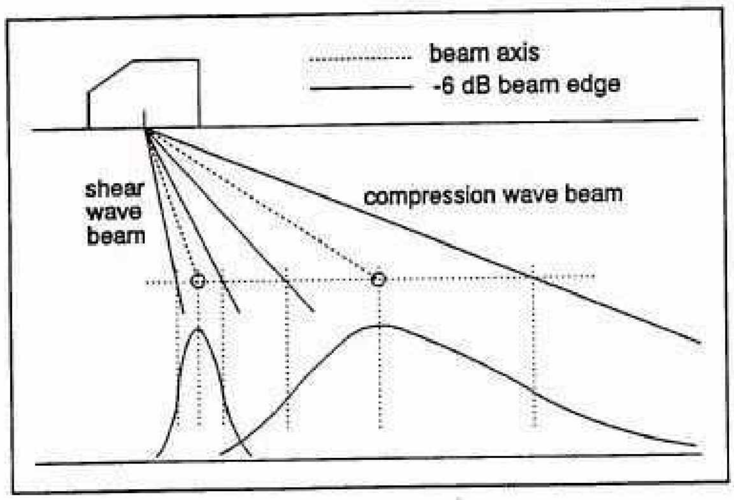


Figure 35 Echodynamic with compression and shear wave beams

As there is a division of acoustic energy between the two wave modes generated by angled compression wave, they do not appear to be sensitive as shear wave probes. For the angles commonly applied for weld inspection, i.e. 45°, 60° and 70°, the percentage of the acoustic energy converted into unwanted shear wave increases with beam angle. Therefore the apparent deficiency in sensitivity increases with beam angle.

The other factors which affect the performance are as follows:

- For a given test frequency compression wave probes have twice the wavelength of shear wave probes. Therefore the beam spread of the compression wave component is twice that of the shear wave component. Secondly, the range resolution of the compression wave component is only half that of the shear wave component
- Compression wave probes are generally only used at ranges up to the half skip distance. This is because the intensity of the reflected compression wave is reduced to a low level by mode conversion to a shear wave upon reflection.

6.1.1.1 Single crystal compression probes

The basic construction of single crystal compression wave probes is similar to that of the well known single crystal shear wave probes, but the wedge angle is much smaller than for a shear wave probe with the same beam angle in the steel. For this reason, reverberations within the wedge are a more serious problem than for shear wave probes. Specific measures to decrease the reverberations can be taken such as increasing the wedge delay and by application of damping material to the wedge. The result of these measures is that single crystal compression wave probes are often relatively large in size.

Figure 36 shows a typical distance amplitude correction (DAC) curve for an unfocused compression wave probe. They have a longer dead time and lower peak sensitivity than twin crystal probes, but they can be used to examine components at much longer ranges than twin crystal probes.

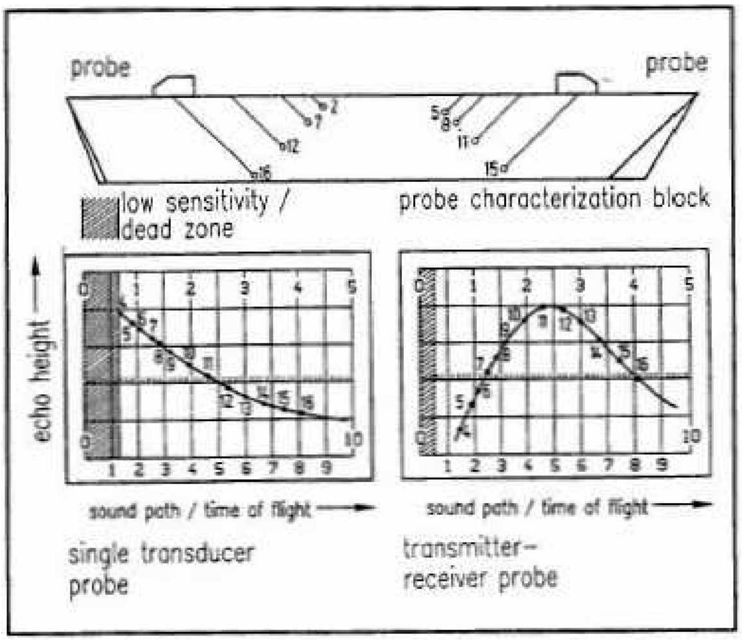


Figure 36 Distance-amplitude correction (DAC) curves for characterisation of a single crystal and twin crystal compression wave probes.

6.1.1.2 Twin crystal compression probes

The crystals in a twin crystal probe are usually inclined to one another so that their ultrasonic beam axes intersect to produce a quasi focusing effect. Figure 37 shows a DAC for a twin crystal probe. At ranges close to the quasi focus the sensitivity and signal-to-noise ratio are higher than those for an equivalent single crystal probe, i.e. a probe with an identical crystal to the transmitter or receiver crystal in the twin crystal probe.

The construction of the twin probe reduces the effect of reverberations within the probe wedge, such that a very short dead zone can be achieved with a probe focused close to the scan surface.

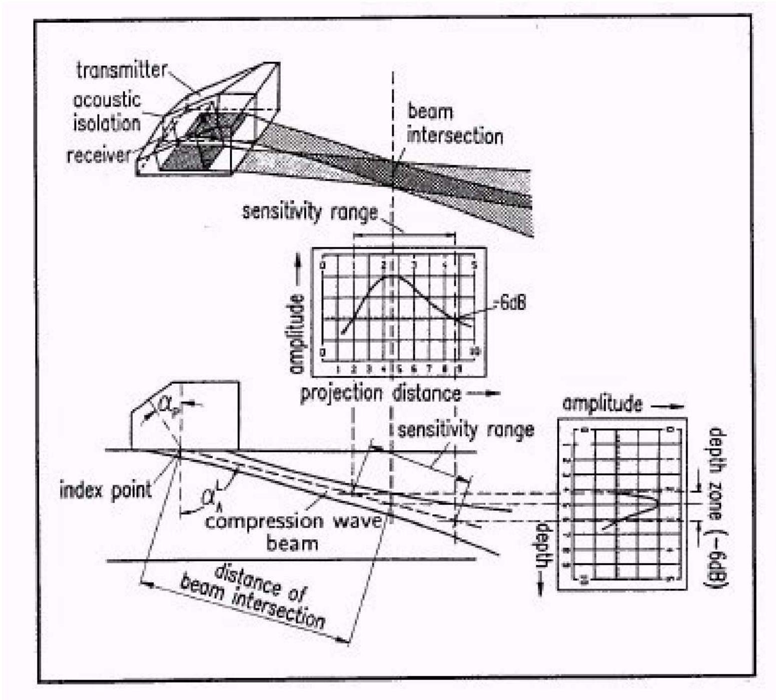


Figure 37 Sensitivity diagrams of twin crystal probes for compression waves

The crystals in a twin crystal probe are usually positioned side by side as shown in Figure 37, but they may also be positioned one behind the other. This figure also shows the amplitude of the beam as a function of distance in two directions, one of which is the DAC.

The disadvantage of quasi focusing is that several twin crystal probes with different focal lengths are required to examine a thick component as indicated in Figure 38.

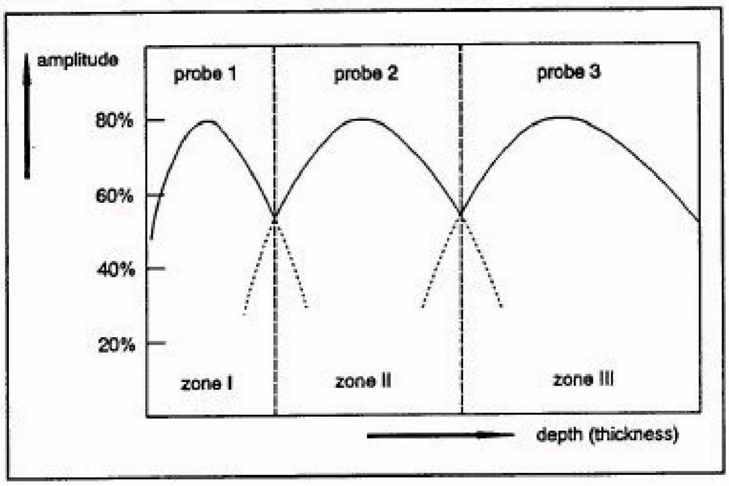


Figure 38 Several probes required to maintain sensitivity over full wall thickness.

A complication, which arises with the twin crystal compression wave probe, is that the beam angle is a function of range for any material. Generally, the beam angle decreases as the range increases. For accurate measurement of flaw location, the beam angle should be measured over the useful range of the probe using side drilled holes at different depths in a test block manufactured from the material to be tested.

Special Probes

6.1.1.3 Creeping wave probes

A derivate of the angled longitudinal wave probe is the “creeping wave” probe. The creeping wave is generated at the first critical angle of incidence and propagates along the surface as a compression wave (Figure 39). Unlike Rayleigh waves, the creeping wave is not damped by couplant on the component surface nor does the beam follow undulations in the surface.

By nature, a creeping wave probe generates

- Compression waves at large angles between 70° and 90°
- Shear waves according to Snell’s law

The surface wave velocity is identical to that of a compression wave.,

Creeping wave probes are very useful for the detection of surface breaking/near surface flaws, since the beam angle of the compression wave component peaks at 75°, but with a significant component parallel to the surface.

Creeping waves decay very quickly with range and for this reason are usually generated by twin crystal probes with short focal length. Creeping wave probes also have a very strong shear wave beam at approximately 33°. This shear wave component converts to a secondary surface wave at the backwall of the component (Figure 40).

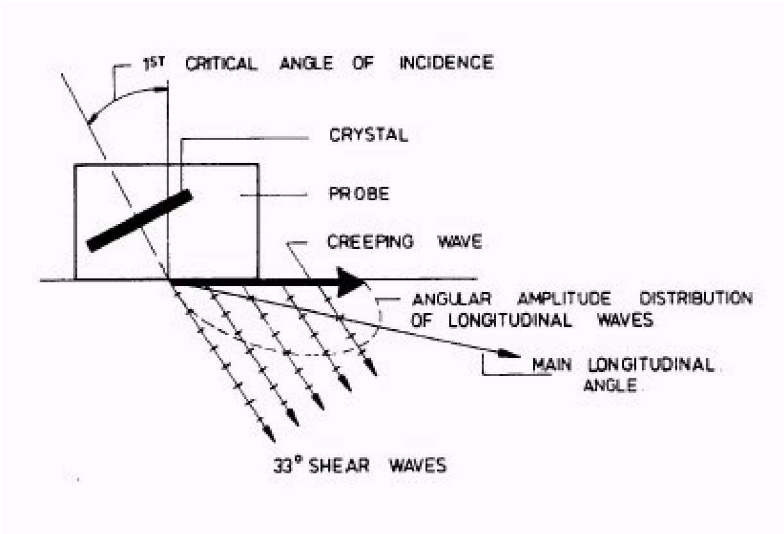


Figure 39 Principles of the creeping wave probe

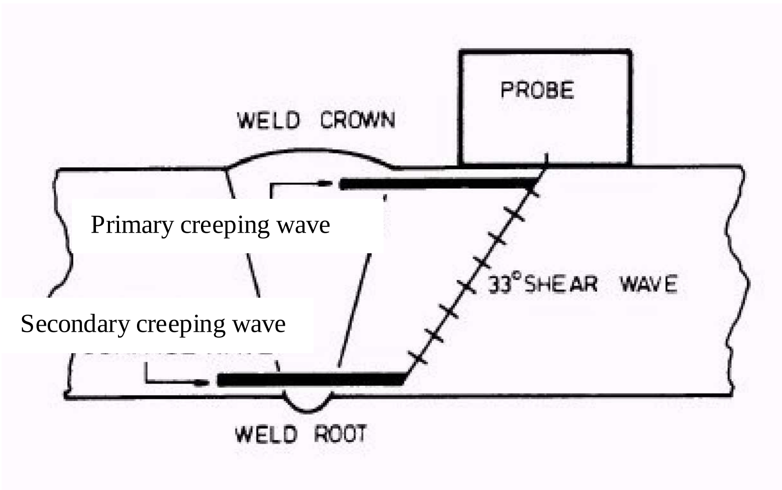


Figure 40 Application of creeping waves

6.1.1.4 Mode conversion probes (LLT)

Different types of mode conversion probes may be used as a substitute of the tandem technique.

The self-tandem mechanism is a useful angled compression wave probe technique for detecting throughwall-oriented planar defects at certain throughwall locations (Figure 41). It is optimised for the detection of defects, which are at best partially at the following depths (with the probe scanned on the outer surface):

45° - 0.71T
60° - 0.65T
70° - 0.61T 'T' is the thickness of the component.

The operator must exercise due care in identifying self-tandem signals since the self-tandem mechanism does not operate in pulse-echo mode and the timebase is generally calibrated for compression wave pulse-echo mode. In order to assist the operator in the recognition of self-tandem signals, and in the distinction from other potential signals, Table 7 defines simple formulae that can be used to calculate the expected ranges for different mechanisms.

The self tandem mechanism may give rise to relatively high amplitude signals from planar defects lying between midwall and the backwall. For self tandem to be possible at least part of the defect must lie within the region of intersection of the direct compression beam and the mode converted compression beam generated by the shear lobe of the probe when it strikes the back surface (Figure 41 and Figure 42). Where the defect is throughwall oriented and crosses the centre of the zone of intersection of the beams, a specular reflection will be detected; where a defect edge (top or bottom) lies within the intersection zone and the defect orientation is within 10 - 15º of the throughwall direction a diffracted signal of relatively high amplitude may often be detected.

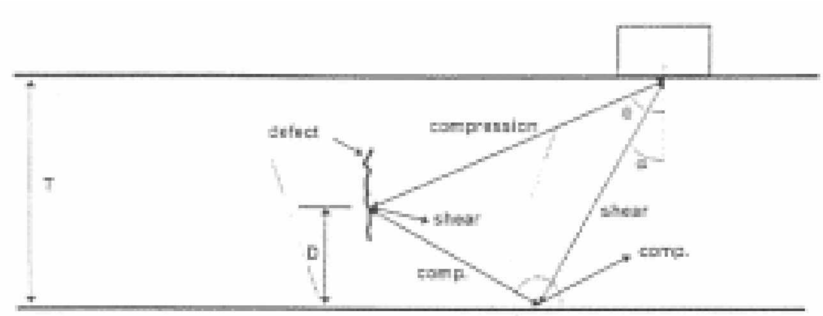
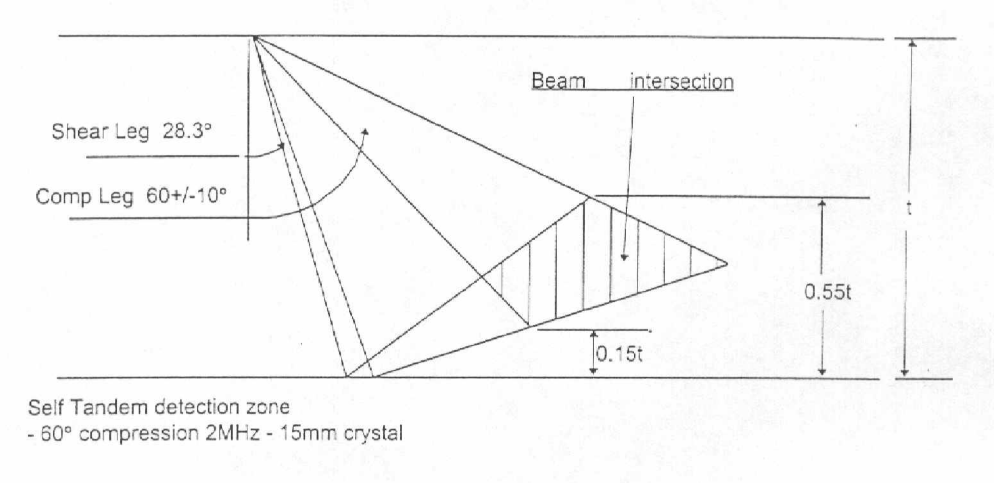


Figure 41 Self tandem mechanism is a useful angled compression wave probe technique for detecting throughwall oriented planar defects at certain throughwall locations

Table 7 Simple formulae that can be used to calculate the expected ranges for different mechanisms

Compression Wave Angle	**Associated Shear Angle**	**Indicated Ranges**			**Optimum Defect Depth (d)**
		Comp. ½ skip	**Shear, ½ skip**	**Self-tandem**	
45°	22,5°	1,42T	1.97T	1,69T	0,71T
60°	28°	2T	2,06T	2,03T	0,65T
70°	31°	2,92T	2,12T	2,52T	0,61T



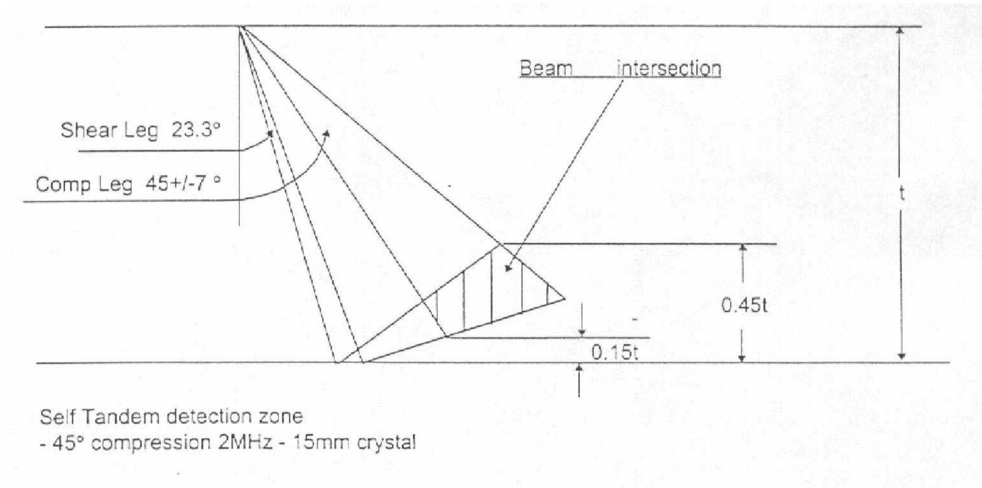


Figure 42 For self tandem to be possible at least part of the defect must lie within the region of intersection of the direct compression beam and the mode converted compression beam generated by the shear lobe of the probe when it strikes the back surface

6.1.1.5 Focused probes

In principle the main advantage of using focused probes for the inspection of acoustically noisy materials is to minimise the volume of material, which is insonified by the ultrasonic beam. This minimises the scattered energy and improves the signal-to-noise ratio compared to an equivalent unfocused probe.

Ultrasonic beams can be focused with curved crystal or lenses in contact or immersion probes (or with phased arrays - section 6.3.3.4).

There is an obvious advantage in using focused probes for sizing flaws by probe movement techniques. However, in the detection phase a much finer scanning pitch is required for a focused probe than for an unfocused probe to achieve 100% coverage of a component. Furthermore, it may also be necessary to use several focused probes to examine a thick component as indicated in Figure 38.

Generally it is possible to produce narrower beams with focused immersion probes than contact probes, since larger crystal sizes are practical for the former. Focused immersion probes must however be used as specified by the manufacturer since they are very sensitive to small changes in the beam angle in water due too the high refractive index at the water/steel interface. Furthermore their sensitivity to flaws can be strongly influenced by the beampath length in water.

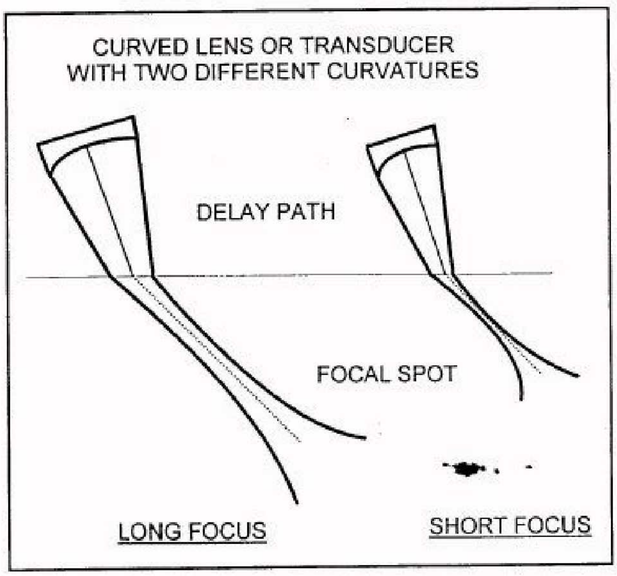


Figure 43 Focused sound field due to a lens or curved crystal

On the other hand when inspecting from the clad side (for example for dissimilar welds), the effect of small irregularities in the cladding layer, such as at the overlap between cladding strips, is less for large diameter focused immersion probes than for contact probes. This is due to the averaging effect of the larger beam diameter of the immersion probes at the cladding surface compared to contact probes.

6.1.1.6 Phased array probes

A Phased Array probe is typically a one or two-dimensional array of small transducer elements. To control the beam characteristics, the excitation pulse is applied at different times to the various elements of the probe. Different Phased Array probe configurations are for example ρ-θ, circular, matrix and linear (appendix 4).

6.1.1.7 EMAT probes

In principle, SH waves can be generated with piezoelectric transducers, but highly viscous couplants are necessary, which makes scanning extremely difficult if not impossible. SH waves can however be generated by electromagnetic acoustic transducers : EMATs.

The principles of EMAT probes are described in appendix 5.

This conception offers several advantages. In addition to the supposedly reduced sensitivity of SH waves to the weld, the absence of couplant, the absence of mode conversion by geometrical reflection and the wide range of adjustability of the angle of incidence.

These advantages are nonetheless counterbalanced by some drawbacks, such as the high sensitivity of EMATs to surface geometry due to large probe size, the lack of overall sensitivity of the technique, making it unfit to characterization, the poor resolution due to the relatively low frequencies achievable (typically $\leq$0.7 MHz; higher frequencies up to 1.8 MHz have been reported, but the instrumentation is so far not fit for current use), the complexity of use and the lack of availability of really industrial instruments.

For these reasons, this technique has been applied only in a few industrial applications, is for the moment limited to laboratory and feasibility studies, and will probably stay so as long as no significant technological progress is achieved in the instrumentation design. Furthermore, intrinsic physical limitations, such as the sensitivity to surface geometry, will always have to be taken into account in the design of tentative applications.

6.1.1.8 TOFD Probes

The basis of the TOFD technique – the detection of tip diffracted signals with low signal to noise ratio – means that it has limited usefulness for austenitic weld inspection (even though it employs angled compression waves). Therefore, it should not be used as the sole inspection technique.

One useful application is the sizing of cracks breaking the scan surface, although capability deteriorates as the crack depth increases.

The choice of probe frequency will inevitably be a compromise between achieving the high resolution needed for accurate sizing (high frequency) and reducing attenuation and noise (low frequency).

The optimum probe parameters are best identified by trials on representative test pieces (in common with any ultrasonic technique for austenitic welds).

Couplant

A couplant, usually a liquid or semi-liquid, is required between the face of the probe and the surface being examined to permit transmission of the acoustic energy from the transducer to the material under test. Typical couplant include water, oil, grease and glycerine. The couplant used should form a film between the probe ant the test surface. It should not be injurious to the material to be tested or disturb subsequent surface treatment.

This is of particular importance in examining austenitic materials where coupling residues may cause problems such as stress corrosion cracking in service. Couplant containing halogens are to be avoided.

7 GUIDELINES FOR THE INSPECTION PROCEDURE

Introduction

The previous sections of the Handbook have presented the problems and issues associated with ultrasonic examination of austenitic welds and described the most useful techniques currently available. This section provides guidance on how to use this information to develop an effective inspection procedure.

It is important for any weld inspection to have clearly defined objectives. Careful consideration of these objectives is important for austenitic weld inspection, given the difficulties described in earlier sections. For example, it needs to be recognised that the smallest detectable defect may be larger than for equivalent ferritic welds.

Previous sections have described the factors that affect the inspection performance. The availability of such information, and the inspection requirements, will determine the approach taken to develop the inspection. .

When detailed information about the weld is available, the most effective way to develop a reliable inspection procedure is to conduct trials on test pieces representing all of the production welding variables (and hence the weld grain structure) and include reflectors representing defects of concern. It may be reasonable to reduce the scope of practical trials by:

- adapting procedures developed for welds with similar characteristics;
- categorising welds in groups where a wide range of weld sizes are to be inspected;
- applying theoretical modelling

It is recognised that in some cases there may be little, or no, information about the details of the weld and the parent material. In such cases, additional activities during inspection development may be required to provide an acceptable performance (which may be demonstrated using the methods described in Section 8). These activities may include studies to determine the effect of a range of parameters on the inspection performance.

In addition, increasing the number of inspection techniques may improve confidence that the examination volume is being adequately inspected

Evaluation of Parent Material

General

Ultrasonic evaluation of parent material adjacent to welds is essential for three reasons:

- to ensure freedom from defects which could inhibit the propagation of angled beams applied subsequently for weld inspection
- to measure the attenuation and enable judgments on inspectability and similarity to any test pieces used to develop the inspection procedure
- to confirm the material thickness and enable the prediction of beam path lengths

For these reasons the evaluation of the parent material is invariably carried out prior to inspection of the weld (Figure 44).

The main objective of this handbook is to describe examination techniques for austenitic welds. The thorough examination of parent material for every conceivable defect is out with the scope; only 0º scans for defects predominantly parallel to the scan surface are considered.

It is worth highlighting that the parent material local to the weld and HAZ (Figure 44) should be included as part of the weld examination volume. Techniques defined for the weld examination are also likely to have useful capability for detecting a variety of defects in this limited volume of parent material.

Techniques for assessment of wrought parent material are given in the following section. For cast materials, the attenuation of the parent material is generally very high and techniques must be developed and demonstrated on a case-by-case basis.

The examination of wrought austenitic parent material is generally carried out using the same techniques as for ferritic parent material. However, in some cases the attenuation of wrought austenitic material may be significant in which case it may be necessary to use a lower frequency than normal for the parent material examination.

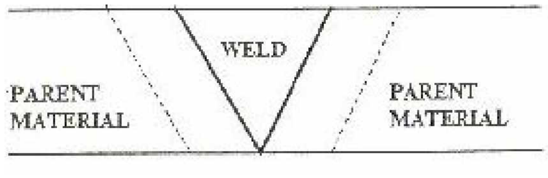


Figure 44 Weld configuration

Techniques for the Examination of Parent Material

Generally, 4-5MHz 0º compression wave probes are adequate but lower frequencies (e.g. 1-2MHz) may be necessary for parent material presenting high attenuation. Twin crystal probes are recommended for thicknesses up to around 30mm a combination of twin and single crystal probes for greater thicknesses.

Typical technique parameters are listed in Appendix 6.

Techniques for Measuring Attenuation

Attenuation measurements are useful in two circumstances:

- ideally, the development of the weld inspection procedure will have been conducted on representative test pieces manufactured with production parent material/parent material of similar grain structure. Attenuation measurements will confirm whether the grain structures of the test piece and production parent material are indeed similar;
- when the weld inspection procedure has not been developed on representative test pieces, attenuation measurements will indicate the inspectability of, and through, the parent material.

Typical methods are described in Appendix 6.

Time base calibration

Sweep range calibration for shear wave probes and 0° compression probes is established using conventional methods and does not need to be discussed here.

For angled compression wave probes, sweep range calibration can be established using either of the following methods:

- by setting velocity using a 0° compression wave probe in the conventional manner, then using the time delay control to compensate for the shoe delay using a radius echo once the angle compression probe is connected;
- by using a minimum of two reflectors at different but known ranges, e.g. calibration blocks with radii 50 and 100 mm .

Sensitivity setting

The most reliable method of establishing reference and scanning sensitivities is to perform trials on fully representative test pieces leading to the identification and optimisation of the most useful techniques. After selecting the probes for a particular wall thickness and weld geometry and determining their characteristics, for example on the probe characterisation block (see section 7.5), the examination sensitivity should be set with the aid of a reference block or using the noise level.

Note that for any given probe it may be necessary to apply different sensitivities for scans in different directions to take account of variations in material properties (e.g. cast-forging weld).

If a reference block is used, it should allow for setting the gain on side drilled holes, notches or other artificial reflectors. In order to optimise repeatability of setting the reference sensitivity the block should not contain a weld and should be made from fine grain, isotropic material. The inspection sensitivity is established by increasing the gain setting from the reference block by a value determined from previous experience, from experiments or from the qualification tests (see section 8). It should be noted that the use of a fine grain reference block does not take account of either beam deviation or attenuation which may occur in austenitic weld metal. The use of a reference block containing a representative weld may account for beam deviation and attenuation. However, it is difficult to achieve repeatability in setting the sensitivity with this type of block. In addition, the grain structure in the reference block may not be representative of the entire weld.

Alternatively, the inspection sensitivity may be set using the noise level. Here the noise (due to grain boundaries) level from a defect free region of the area of interest is measured and indications that exceed this by a specified amount are recorded. Care should be taken to ensure that material noise is measured as opposed to other external sources of noise.

In any case, the sensitivity should be verified on representative specimens containing ideally real defects or, at lest, artificial defects (like EDM notches) with known dimensions.

Probe characterisation

Introduction

Figure 45 shows a typical block for equipment characterisation. It includes side drilled holes, infinite reflectors at fixed angles and notches.

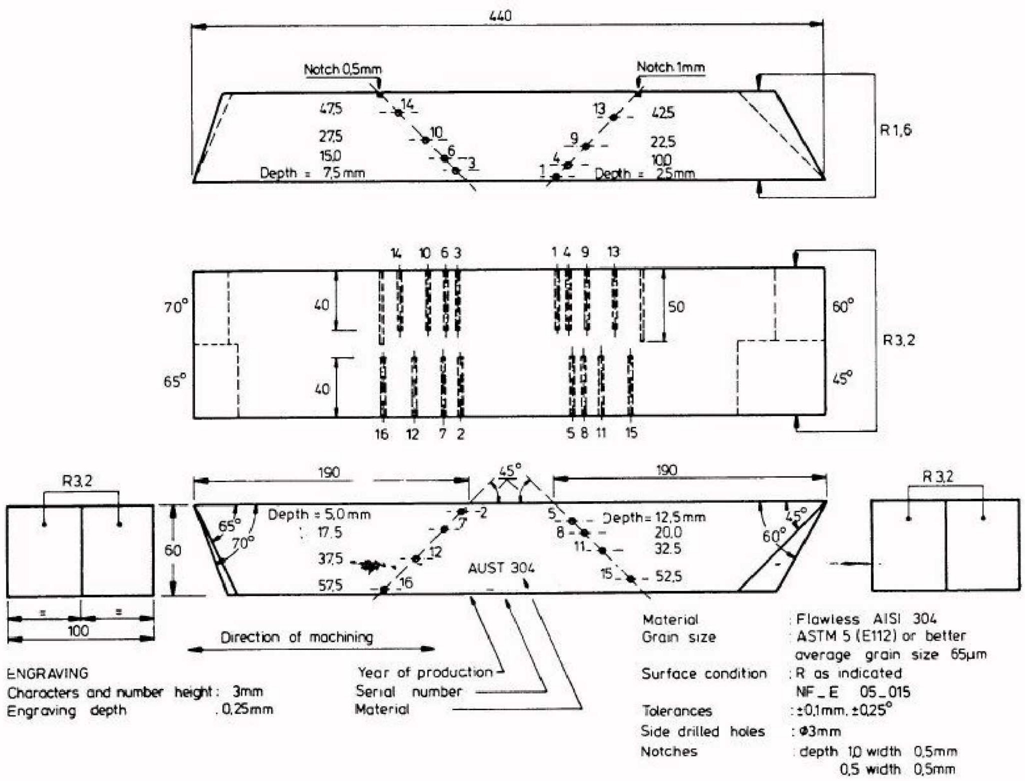


Figure 45 Probe characterisation block

Although it is well known that acoustic behaviour in welds is different from that in parent material, it is valuable to know the basic characteristics of the probe under ideal conditions. With the aid of such a block, a number of characteristics can be established, such as:

- distance amplitude curve (or focal curve)
- check of the nominal focal distance marked on the probe
- check of the nominal probe angle marked on the probe
- beam spread
- zone height (for focused probes)
- probe angle as a function of distance
- bandwidth of the probe
- nominal signal-to- noise ratio

The holes should be situated in such a way that minimum interference is caused by the associated shear wave beam of a longitudinal probe reflecting from adjacent holes.

This block has a series of holes at different depths, which provide enough data points to draw a smooth amplitude distance diagram. The various holes are necessary because:

- the pronounced distance amplitude characteristic, particularly for TR probes, requires a hole at the approximate working depth of the probe in order to set the sensitivity
- the apparent probe angle of compression angle beam is dependent on transit distance. The nominal probe angle of TR probes can only be checked on a hole at approximately the nominal “focal” distance. At short distances, the apparent angle is greater than the nominal angle, while at longer distances the angle decreases.

As an alternative, the blocks described in different standards can be used to establish the characterisation.

When the appropriate type of probe has been selected, e.g. single crystal angled compression wave, focused compression wave, angled shear wave, etc., it is necessary to determine the probe characteristics in detail (even when nominally identical probes are used). For the specialised probes frequently needed for austenitic inspection, manufacturers may provide data sheets describing either the nominal specification or the actual performance claimed for a particular probe under standardised conditions.

This paragraph provides guidance on methods, which can be used to determine the characteristics of different kind of probes. The properties determined are referred to as probe characteristics but they are in fact also influenced by the electronic part of the test equipment. It is therefore essential that measurements are performed with a thoroughly checked flaw detector properly calibrated with regards to linearity, etc.

In spite of these precautions, one should be aware of the fact that the probe characteristics may change when the probe is used on coarse grain austenitic materials.

For angled longitudinal wave probes, it is also essential to measure the angle of the shear wave, which accompanies the desired longitudinal wave beam.

Extra measures are required to characterise contact probes for use on curved surfaces. Special blocks may also be needed for the accurate determination of some of the characteristics of focusing probes for critical operations.

Probe index of angled longitudinal wave probes

The probe index is the first probe feature, which should be determined before any determination of beam angle or beam profile is made.

Because of the existence of shear wave beam, only the first reflection should be used when calibrating longitudinal wave probe with these blocks. It has been observed in practice that the shear wave beam can have a different index point from the longitudinal wave beam. The probe index point(s) should be permanently marked on the probe and must be checked from time to time during examination because of possible changes due to shoe wear.

Alternative calibration blocks with full quadrant radii are necessary for probes with beam angles less than 40°.

Distance amplitude curve

By using a series of holes at various ranges and maximising the echo amplitude for each, it is possible to draw the distance amplitude curve. Focusing or TR probes require a hole close to the appropriate working depth of the probe. A typical distance amplitude curve is shown in Figure 46.

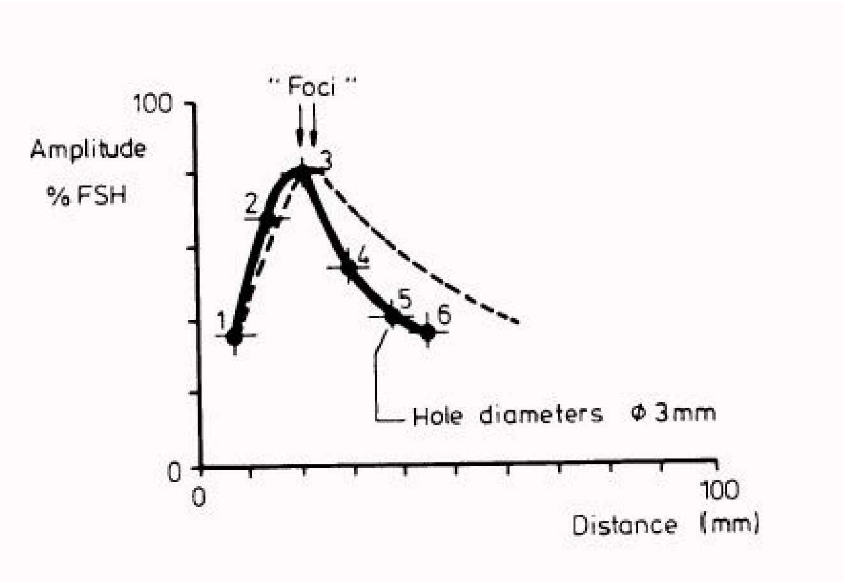


Figure 46 Typical distance amplitude correction curve (for a 70°TRL probe) measured using holes 1 to 6 in the probe characterization block in Figure 45.

Beam angle

For angled longitudinal wave probes, there are two beam angles to be measured, that for the longitudinal wave beam and that for the associated shear wave beam.

Due to the occurrence of mode conversion into shear waves, notches produce a weak echo, which make them difficult to use for the determination of the beam angle of longitudinal waves.

The apparent beam angle of TR angle beam probes is dependent on transit distance. The nominal angle on these probes can only be checked on a hole at nominal focal distance. At shorter distance, the angle is larger; at longer distances, the angle is smaller than the nominal angle. Therefore, for accurate probe characterisation, an angle versus distance diagram should be determined.

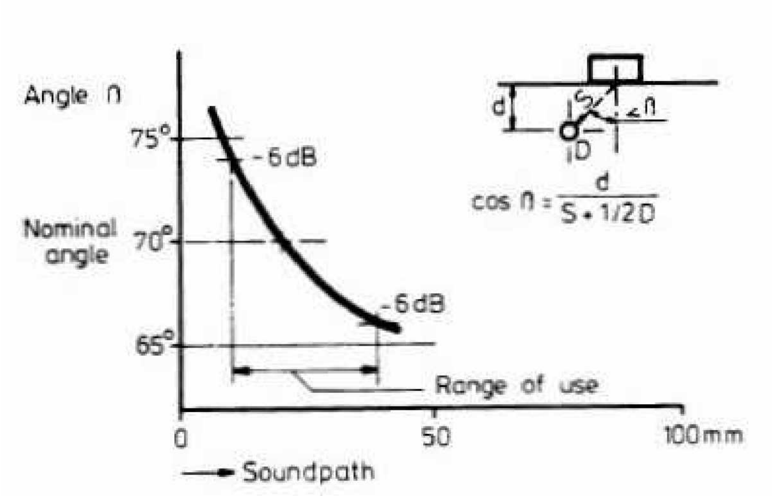


Figure 47 Typical relation between apparent beam angle and soundpath

Beam width

Using a series of reflectors at various ranges and determining also the probe movement for 6 dB reduction in amplitude from the maximum value, the procedure may be extended to plot the vertical beam profile. It is recommended that the profile should be plotted at an appropriate level of working sensitivity to allow the side lobes to be assessed.

From the beam profile, an estimate can be made of the focal distance for TR and focusing probes. However, special blocks will normally be required for determination of the precise characteristics of probes for critical applications.

The occurrence of "squint" may be recognised by the need to twist the probe measurably in order to maximise the signal.

Amplitude behaviour for different reflectors (for TRL or focusing probes)

One very important fact is to be mentioned: when making a reference curve of amplitude versus distance using infinite plane reflector, the maximum sensitivity may be reached at a distance which differs from that for curves established using side drilled holes.

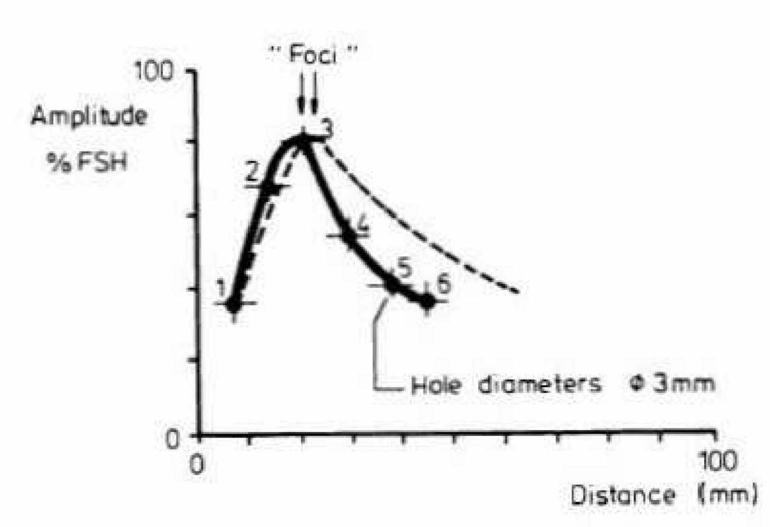


Figure 48 Comparison between typical distance amplitude correction curves constructed using side drilled holes and an infinite plane reflector perpendicular to the beam. Note that the dotted line associated with the infinite plane reflector has been plotted with a 12 dB lower sensitivity.

Furthermore, the difference in sensitivity between the curves constructed using different reflector is most important.

A large difference in amplitude between infinite plane reflector and holes means better amplitude discrimination between small and large reflectors.

Estimation of dominant frequency and bandwidth

Exact determination of the dominant frequency and bandwidth is only possible by signal analysis.

These properties are strongly influenced by material characteristics, sound path, and type of reflector. However, they can be estimated approximately by straightforward method, which is good enough for most practical applications.

To measure the dominant frequency f_r, a flaw detector with an unrectified display may be used. The time base is first calibrated for a beam path length covering the range of interest. The echo of a calibration block radius is brought into the calibration range of the time base, and the frequency f_r is estimated by counting the number of cycles N over a given sound path S in mm. The velocity c for which the time base is calibrated has to be known in mm/s/.

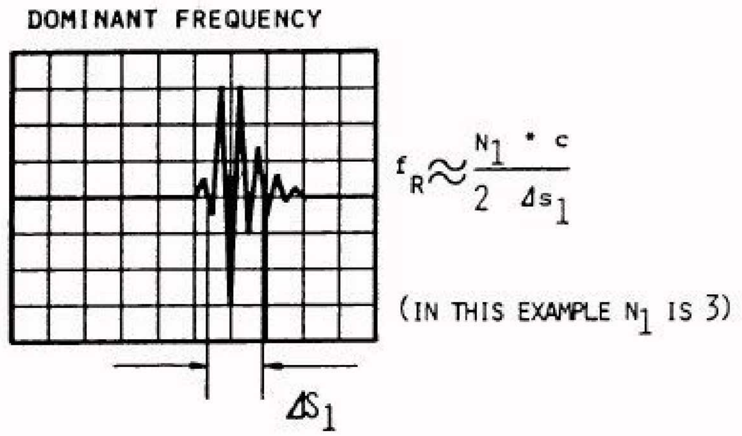


Figure 49 Estimation of dominant frequency f_r

The bandwidth f_b should be established in relation with to the dominant frequency. The bandwidth can be estimated by counting the number of cycles N of the complete echo of a block radius surface set at the FSH (or other suitable height).

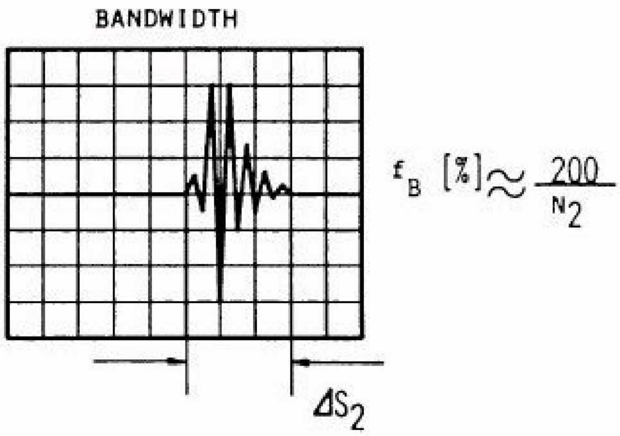


Figure 50 Estimation of bandwidth f_b

Dead zone and near field

A probe characterisation block can be used to check the dead zone of a probe by observing the echoes from the near surface notch and from holes, which are at intervals of 5mm from 2 to 5 mm and determining which is the nearest echo, which can be determined.

These holes can also be used to explore the variation of sensitivity within the near field and ascertain whether a range of interest happens to coincide with a region of sufficient sensitivity.

Nominal signal to noise ratio

A comparison of probes with regards to their noise level (i.e. amplitude of spurious probe indication for ranges of interest may be made in the following way:

- set the noise suppression on the flaw detector to zero
- place the probe on a characterisation block and set the echo of a selected reflector to a predetermined height, read attenuator
- while keeping the probe on the block, adjust the attenuator until the maximum noise indication in the range of interest reaches the same height as the target echo level selected above, read attenuator
- the difference between the two attenuator readings gives the required value.

Evaluation level

It is not the purpose of this handbook to define acceptance criteria or an evaluation level for austenitic weld inspection, since these should be agreed between the relevant parties .

The procedure should recognise the increased risk of spurious indications and define these where representative test pieces are available.

Characterisation of Indications

The process of characterising indications should include location, sizing and determination of the origin of the indication.

Characterisation of indications in austenitic welds is more difficult in austenitic welds (than ferritic) due to the anisotropic grain structure, high attenuation and lower signal to noise ratios.

The first decision that has to be made is whether the ultrasonic indication comes from a real defect or whether it is due to some spurious origin. The potential for spurious signals is more severe than it is for ferritic material due to:

- The shear wave associated with the compression wave probe
- Mode converted signals are more numerous when angle compression wave probes are used
- Fusion face reflections due to the acoustic mismatch between the parent and the weld materials
- Localised regions of high noise due to grain boundary scattering

Figure 51 shows some potential sources for spurious signals.

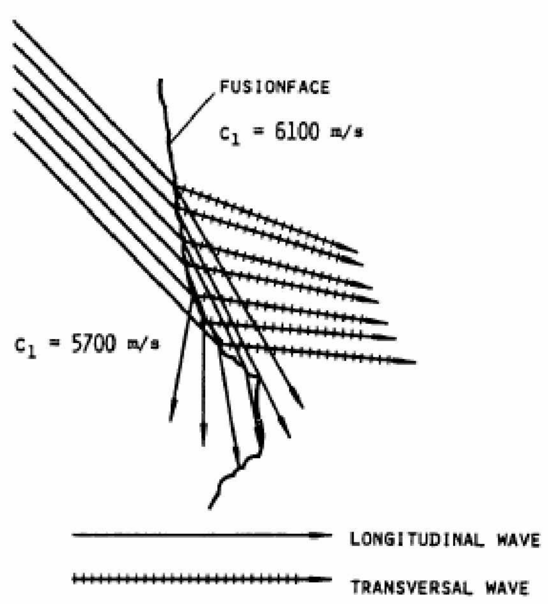


Figure 51 Potential sources for spurious signals

When assessing the nature of indications, it is necessary to use all the information available about the component and to evaluate the indication for each beam accordingly. If it is not clear from the data available whether the indication is from a defect or not, then either more data is required from additional scans or techniques, or the signal must be classified as having a defect origin.

If the signal is identified as having a defect origin then the next important stage of evaluation is to characterise the defect as planar or volumetric. As in the case of ferritic materials this characterisation is based upon the information gathered from several probes, in particular the signal amplitude and echo dynamic behaviour. However, the practical situation in coarse grain austenitic materials is more complex due to the following:

- The attenuation through the material is relatively high and uncertain. This means that the measured amplitude of the signal cannot be used as reliable indication of the defect type
- The variable attenuation and grain boundary scatter modulate the echo dynamic pattern. Therefore, as an example, the response from a smooth planar defect with a beam at normal incidence may not have a regular pattern and echo dynamic as it would for ferritic materials
- The spatial and temporal resolution of low frequency compression waves probes reduces the ability to perform accurate characterisation
- Low signal to noise ratio may obscure some defect signals (e.g. tip diffracted echoes) that would assist in this discrimination process.

When using shear waves, a corner effect exists for surface breaking defects but it is not always the case with compression waves. Other techniques may be used, for example tip diffraction, but some techniques may have strong limitations due to the anisotropic properties of the materials.

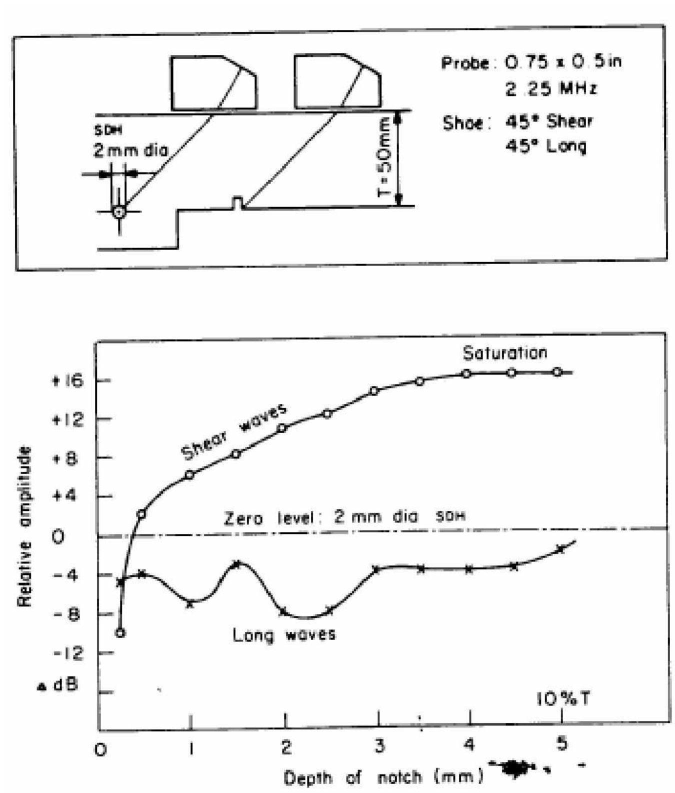


Figure 52 A corner effect exists for surface breaking defects when shear waves are used but it is not always the case with compression waves.

Defect Sizing and Location

The techniques available for sizing defects in austenitic welds are generally the same as for ferritic welds. In most cases, defect sizing demands additional techniques to the ones used for detection.

It is generally acceptable to determine the length of indications by conventional sizing techniques such as 6dB drop.

One accurate technique for throughwall sizing is measurement of diffracted signals from the crack/defect boundaries. However, these signals are naturally weak (low signal to noise ratios) and may not be detected by traditional TOFD techniques. If the tip diffraction technique is to be applied then it should be conducted using probes with appropriate characteristics.

When an ultrasonic wave strikes an elongated crack like flaw or a lack of fusion type defect the return wave front is a combination of reflected signals and cylindrically diffracted signals radiating from the tips of the defect. These diffracted signals are of relatively low amplitude but are emitted in all directions along the same plane as the instigating ultrasonic wave.

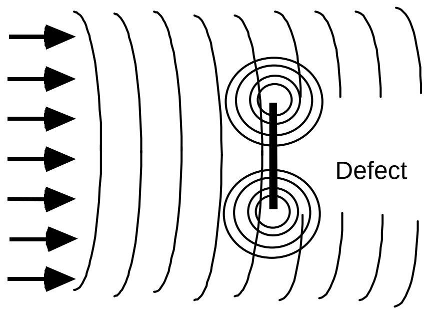


Figure 53 Representation of the diffraction process

Different types of concepts can be applied like “back-scattering” or “forward scattering”.

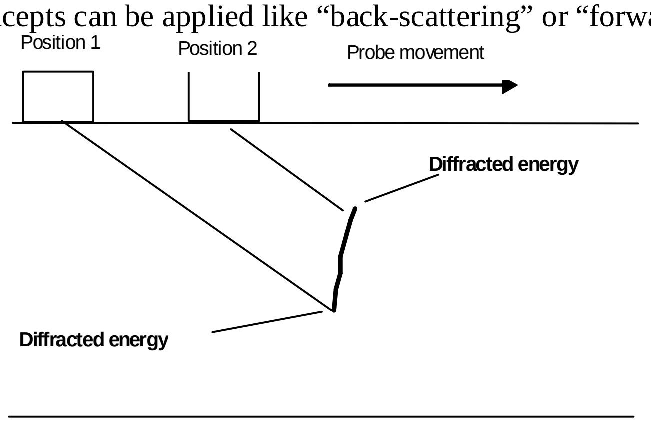


Figure 54 Example of back-scattering diffraction

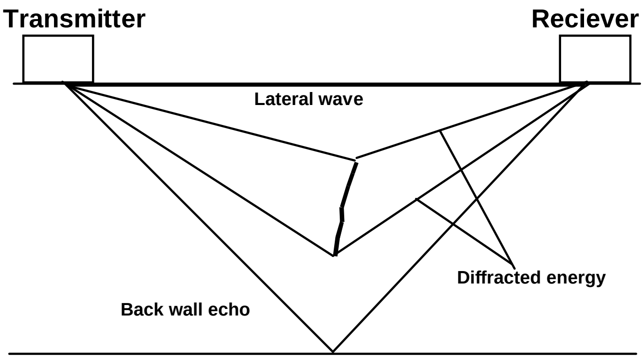


Figure 55 Typical Time of Flight Diffraction arrangement (forward scattering)

Whatever set-up chosen, the diffracted signals are very weak. This puts special demands of the UT-system used.

Any type of diffraction method has to be used with great care in anisotropic materials. Where applicable, the technique can be very accurate.

If defect sizing is needed, it is of importance to demonstrate the capability of the chosen technique on test blocks with representative defects.

Procedure

- The aim of an inspection procedure is to describe how to perform an inspection in a consistent, repeatable and reproducible way. For this reason the minimum content should be as follows:

Scope

Short description / data regarding:

- object, weld type, geometry
- inspection technique(s)
- purpose of the inspection (detection, characterisation etc.)
- defect type(s) and defect orientation(s)

References

References to under laying documents, for example standards, instructions, reports and drawings.

Personnel

Qualification demands for the participating personnel.

Description of the object

- geometry details
- surface demands; i.e. surface finish, weld crowns etc.
- accessibility

Equipment

7.1.1.1 Manipulator

- description of the manipulators to be used (type(s))
- information about the controls / checks which have to be performed before inspection starts
- important variables, including tolerances

7.1.1.2 Data acquisition system

- description of the equipment to be used (type(s))
- software as well as version
- important variables, including tolerances

7.1.1.3 Evaluation system

- description of the equipment to be used (type(s))
- software as well as version

Probes

- description of the probes to be used
- important variables, including tolerances for example:

- manufacturer
- type
- size
- type of connectors
- crystal material
- crystal size

All variables specified should be judged if and how they influence the capability of the inspection system to detect, characterise and size defects.

Couplant

- Specification of couplant to be used.

Cables

- specification of cables to be used, preferably including a sketch
- specification of connectors
- important variables, including tolerances

Calibration

7.1.1.4 Probe measurements

7.1.1.4.1 Probes

- sound exit point, angle, index delay is measured
- parameter settings, calibration blocks and reference reflectors are given
- documentation of performed calibration
- reference block(s)

7.1.1.5 Sensitivity setting

- description of parameter settings, reference blocks and reference reflectors
- documentation of performed calibration

7.1.1.6 Calibration control

7.1.1.6.1 Performance

Calibration control is performed in order to ensure that the sensitivity is the same / within specified tolerances. Intervals between the checks are given.

- description of parameter settings, reference block and reference reflectors
- documented results:

  - for UT/PE at least sound path and signal amplitude
  - for UT/TOFD at least lateral wave /or back wall position, position of signal from reference reflector

7.1.1.6.2 Acceptance criteria

- Tolerances for sound path, amplitude etc shall be given

Inspection/Data Acquisition

The following is given:

- parameter settings
- co-ordinates in relation to inspection area defined
- reference point and starting point for scanning
- scanning pattern, raster size
- maximum scanning speed
- inspection volume, scanning surface (preferably a figure)
- probe position
- file identification

Evaluation

Indication characterization, and sizing when required, have to be achieved and the results have to be compared to acceptance criteria.
It is not the purpose of this handbook to define acceptance criteria for welds. Acceptance criteria are established between all the parties involved in accordance with the inspection requirements and written in the procedure.
In general, they are specified in terms of signal amplitude (relative to recording level), indication height, indication length, number of indications, and position within the weld.
Height and length can be estimated using standard methods for ferritic steels, keeping in mind that the performance can be strongly affected by the microstructure of the inspected weld (see chapter 7.6.2).
False indications or geometrical indications may occur. It may help the evaluation of questionable indications to use a variety of probes or complementary techniques (such as signal processing,) together with accurate plotting of the indication location.

Reporting

The examination results should be given in a report which includes all the necessary information required to:

- make decision on the acceptance of the defects revealed
- facilitate repairs of non-acceptable defects
- permit the examination to be repeated by the same or another operator.

A report / protocol should include the following information (minimum):

- identification of inspection area
- procedure identification including revision
- inspection limitations
- deviations from the procedure
- personnel and their qualifications
- manipulator (if any)
- data acquisition system (if any)
- data evaluation system (if any)
- probes, couplant
- identification of the reference blocks
- method of sensitivity setting and value
- inspection result(s); i.e. type of relevant defect as well as defect length, height and position
- non-relevant defects are reported with a motivation
- date and place for inspection

•

8 INSPECTION QUALIFICATION / PERFORMANCE DEMONSTRATION

The capability of a procedure to detect and to size flaws and the capability of an operator to implement I can be tested with validation or performance demonstration.

The European Methodology for Inspection Qualification (ref.XXX) contains guidelines for such a qualification.

Qualification as defined in this document is a combination of technical justification and test pieces trials using deliberately defective test pieces.

Technical justification involves assembling all supporting evidence for test capability, i.e.:

- results of capability evaluation exercises
- feedback from experience
- applicable and validated models
- physical reasoning

Test pieces must be made using the same manufacturing procedure as used for the component to be inspected and the flaws must be realistic as possible and acoustically simulate those that occur in the component. Furthermore, the dimension of the flaws must be known to an acceptable degree of accuracy.

Prior to start the inspection qualification, all necessary input information for the qualification must be available.

These input are typically:

- objectives of the inspection qualification
- description of the component to be inspected
- type and dimension of the defects to be detected and/or sized
- inspection performance to be achieved

9 GENERAL RECOMMENDATIONS AND CONCLUSIONS

Ultrasonic examination of austenitic welds remains difficult but inspections are possible in many cases. However, all parties must be aware that sensitivity is invariably inferior to that achievable on a ferritic weld of comparable thickness.

In view of the reduced capabilities, fracture mechanics studies should be initiated at an early stage to provide estimates of tolerable defect sizes and to identify regions for ultrasonic coverage. The ultrasonic procedures can be devised to take account of fitness for purpose criteria, rather than to attempt to detect small defects, which will be without structural significance. It should be remembered that even the detection of large defects might require high sensitivity, together with an adequate number of beam angles.

- Inspection capability varies significantly with weld process and procedure.
- Designers should be aware of the major factors, including weld process and geometry that will influence inspectability.
- Operator qualifications and specific training on austenitic welds are especially important.
- Proper attention to combined equipment characteristics and probes can be of significant benefit in ultrasonic weld inspection.
- Performance demonstration of the procedure is of primary importance and often requires practical trials. These activities make austenitic weld inspection more expansive than ferritic weld inspection, and early planning is required

Further development of the techniques is still required and is continuing. It is important to keep up to date with developments in this area.

The techniques described in this handbook could provide valuable solutions in many situations. However, they have to be regarded as guidance for the technical solution in each specific case.

Appendix A1

Reflection and Refraction

This appendix discusses the reflection and refraction of ultrasound at boundaries between anisotropic weld and fine grain base material. Much of this appendix is contained within the main text of this handbook but provides a more thorough treatment for the interested reader.

Throughout this appendix it is assumed that the grains in the weld metal are perpendicular to the fine grain base metal, so that they are in the plane of sound incidence and that the weld/fine grain interface is smooth.

1. Effects of boundaries on wave propagation

In the presence of weld metal several boundaries may influence the propagation of ultrasound with the effect depending on whether the inspection is performed from the weld metal or from the base metal of the component to be inspected. The following effects are encountered :

- Refraction at the weld surface;
- Refraction and reflection at the fine grain-weld metal interface.

The coupling layer between the ultrasonic probe and the weld surface, and the interface between the weld and the fine grain base, are boundaries between acoustically isotropic material and anisotropic material.

The three wave modes (one compression and two shear) that may propagate in acoustically anisotropic materials have their particle displacements (polarizations) in general, neither in the plane of sound incidence, nor in the plane perpendicular to it. Therefore, at an interface all three wave modes may have common components of particle displacement (polarization). Consequently coupling between the separate modes may occur at an interface. The propagation directions of the reflected and the refracted waves are derived from Snell's law as applied to anisotropic materials. To determine the quantity of the reflected and refracted waves it is more meaningful to consider energy, rather than pressure, reflection and refraction coefficients since the energy flow is generally in a different direction to the wave vector direction.

Appendix A2 shows that for the case where the plane of polarization is perpendicular to the plane containing the columnar grains (horizontally polarized shear waves) there is no coupling to any of the other wave modes. Consequently only reflected and refracted Sh waves are generated at a boundary for an incident Sh wave. Conversely, compression waves and Sv waves are coupled at an interface and so the following combinations may exist :

- Incident compression wave; refracted and reflected compression waves and refracted and reflected Sv waves;

- Incident Sv waves; refracted and reflected Sv waves and refracted and reflected compression waves.

In the case considered here the Sv wave has its polarization in the plane of the columnar grains (the plane of sound incidence).

The refraction and reflection phenomena are similar to those encountered in isotropic materials except that the calculation of angles and amplitudes is complicated by the presence of the anisotropic grain structure of the weld metal.

2. Snell's law

Snell's law states that :

- Incident, reflected and refracted waves all lie in the same plane and so the wave normal of all reflected and refracted waves must be in the plane containing the incident wave normal and the normal to the interface.

- Incident, reflected and refracted waves must all have the same component of the wave vector, k, tangential to the surface.

Since the slowness surface is the inverse of the phase velocity, as a function of the wave vector direction, Snell's law can be applied for both isotropic and anisotropic materials using the slowness surface and a simple geometric construction.

For the case studied in this appendix, Figure A1.1 shows the geometrical construction of Snell's law for refraction of shear waves at the fusion line (fine grain – weld interface) for waves incident from the base metal.

Since the reflected and refracted waves must have the same component of k tangential to the interface and since $k \sim 1/Vp$ then the component of slowness parallel to the interface must be the same for the reflected and refracted waves. Therefore the phase velocity of the refracted and reflected waves can be easily derived for anisotropic cases. Also the group velocity can be obtained by constructing the perpendicular to the slowness surface.

Figure A1.2 shows how the refracted directions of phase and group velocities vary for both wave modes generated by a Sv wave incident from the fine grain metal. As an example the left insert of Figure A1.2 shows that for a 30° shear (Sv) wave incident from the fine base metal there is :

- A refracted compression wave

- A refracted shear wave with a negative angle

Note that for certain angles of incidence there are two refracted quasi-shear waves indicated by qSv and qSv(2). These are discussed further in the following sections.

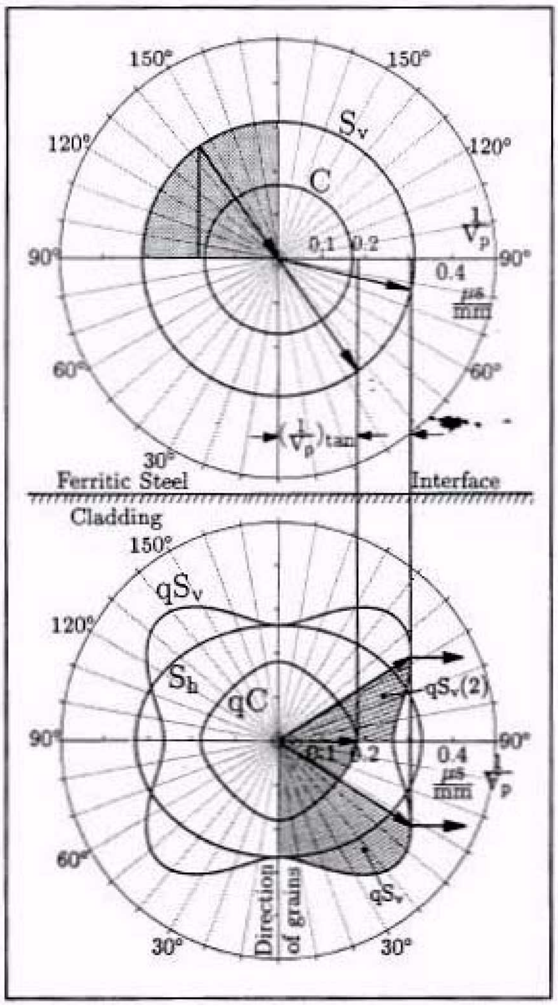


Figure A1.1 – Slowness surface construction of Snell's law for a fine grain – weld interface with the grains normal to the surface and the Sv wave incident from the fine grain material. Only qC and qSv waves couple into the weld, the Sv wave does not couple. The shaded sectors show the incident and the refracted wave vectors which are permitted. Wave vector angles larger than 90° are permissible for the second quasi-shear wave qSv(2). The beam directions are indicated for the critical angle of both quasi-shear waves.

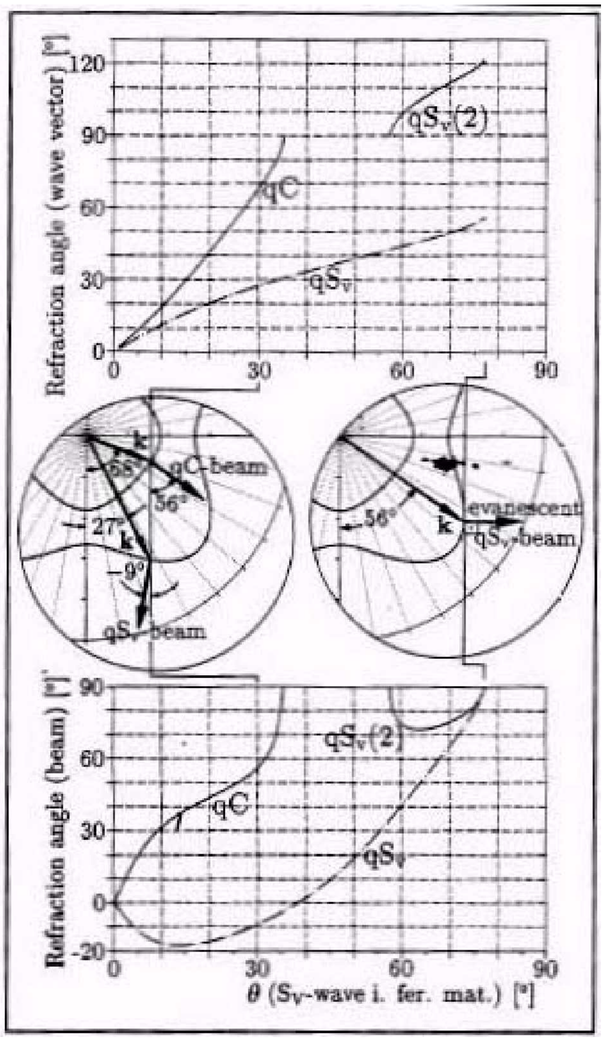


Figure A1.2 – Direction of refracted phase and group velocities in the weld versus Sv wave incidence angle θ in the fine grain metal.

3. Critical angles

The critical angle phenomenon is significantly more complicated for the acoustic anisotropy encountered in austenitic welds than for the purely isotropic cases.

The parameter that determines whether or not a refracted wave can propagate at an interface is the group velocity direction. Thus although the phase velocity (or wave vector k) direction may have a refracted angle of less than 90°, see right inset of Figure A1.2, the group velocity (or beam) direction which dictates the direction of energy flow, may be greater than 90° in which case a refracted wave cannot exist. Only in cases where the group velocity direction is less than 90° a refracted wave can exist. The special case of the group velocity direction equal to 90° corresponds to the critical angle of the quasi-shear wave qSv.

Again using the example of a Sv wave incident from the fine grain base metal, Figure A3.1 shows the situation where there is no longer an intersection of the compression wave slowness surface for the weld. In this case, which is the critical angle for compression waves, the wave travels parallel to the interface with the particle displacement decaying exponentially away from the boundary. This is an evanescent wave. As the incident angle is increased further a second critical angle is reached, which belongs to a second quasi-shear wave referred to here as qSv(2). The angle for the phase velocity direction for this wave is greater than 90° (wavefronts pointing back into the fine grain material) but the angle of the group velocity direction is less than 90° and so it propagates into the weld. Figure A1.3 shows as an example the group velocity direction and the wavefronts for the two components of the quasi-shear wave in the weld generated by a Sv wave incident from the fine grain base metal under an angle of 75°. The energy associated with this second component of the quasi-shear wave is discussed in the next section.

The vertically polarised quasi-shear wave has the peculiarity that the permissible domain of its phase velocity direction in the clad material is separated into two regions, corresponding to the two components of quasi-shear wave. This is shown in Figure A1.1 where the shaded regions represent those parts of the slowness surface where:

- A solution exists for the geometrical construction of Snell's law
- The angle of the group velocity direction is less than 90° (condition for refraction)

Note that this phenomenon also occurs at the interface between the perpex wedge of an ultrasonic probe and the weld, see also Figure A1.16.

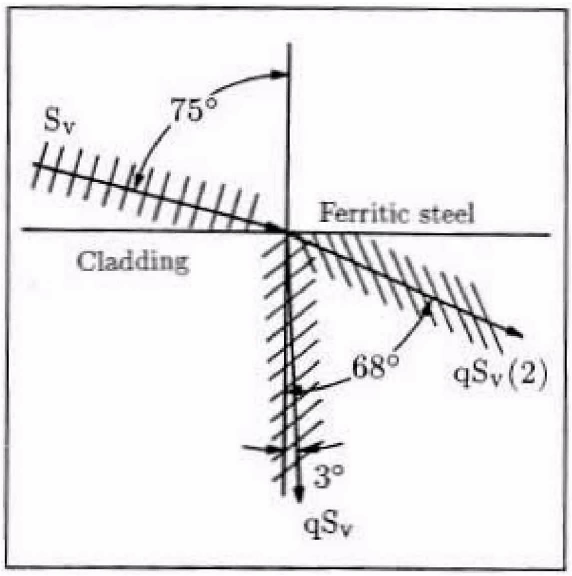


Figure A1.3 – Ultrasonic qSv beams and their wave fronts in the weld for a 75° Sv wave incidence from the fine grain material.

4. Energy reflection and refraction coefficients

In addition to knowing the propagation directions it is also important to know the efficiency with which the ultrasound can be transmitted across the interface.

4.1 The weld - fine grain interface

The calculation of reflection and transmission coefficients at the weld - fine grain interface leads to the following conclusions :

The case of Sh waves is the most straight forward since there is no coupling to either of the other wave mode types. Energy transmission is nearly 100% over a large range of angles of incidence for waves incident from both the fine grain and the weld side, see Figure A1.4 and A1.5.

The compression wave, incident from both isotropic and anisotropic sides (see Figures A1.6 to A1.9) is also found to penetrate the interface effectively over a broad range of angles. Mode converted and reflected energy is less than 5% of the incident compression wave energy for angles up to 70° therefore the problem of spurious indications from the fusion face is not significant.

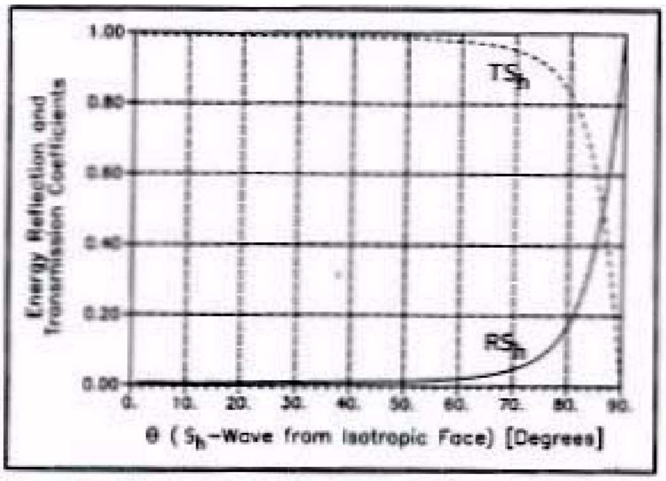


Figure A1.4 – Energy reflection and transmission coefficients for a horizontally polarized shear (Sh) wave incident at the weld – fine grain interface from the fine grain base metal.

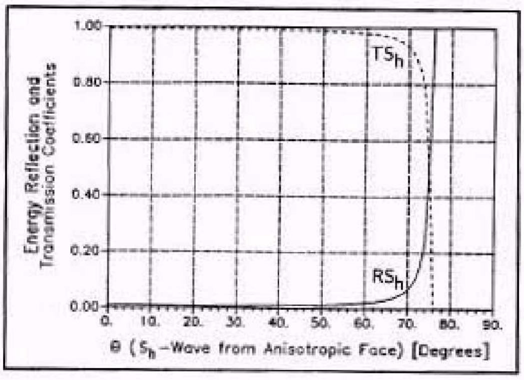


Figure A1.5 - Energy reflection and transmission coefficients for a horizontally polarized shear (Sh) wave incident at the weld – fine grain interface from the weld.

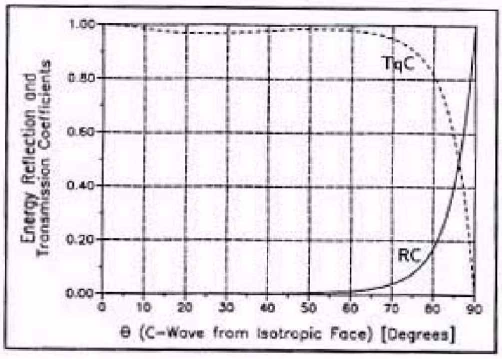


Figure A1.6 - Energy reflection and transmission coefficients for a compression (C) wave incident at the weld – fine grain interface from the fine grain base metal.

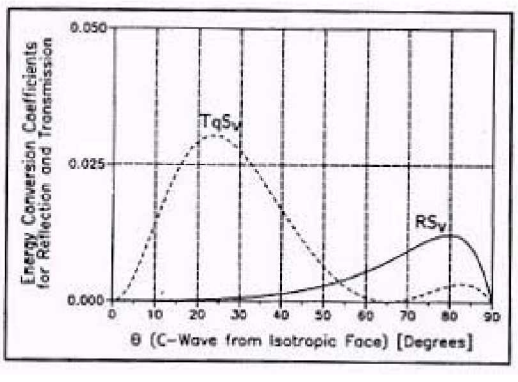


Figure A1.7 – Energy conversion coefficients for reflection and transmission for a compression (C) wave incident at the weld – fine grain interface from the fine grain base metal.

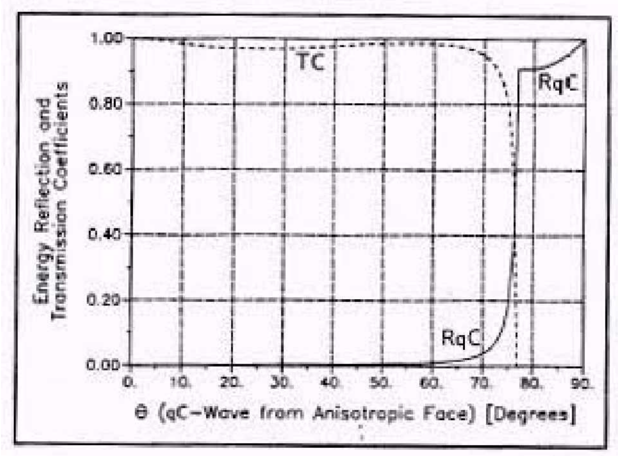


Figure A1.8 - Energy reflection and transmission coefficients for a quasi-compression (qC) wave incident at the weld – fine grain interface from the weld.

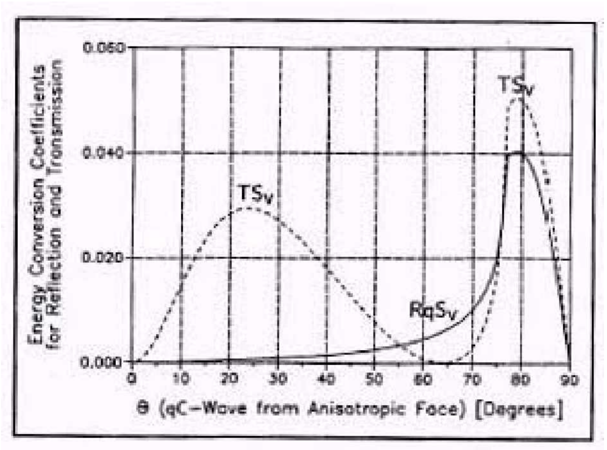


Figure A1.9 - Energy conversion coefficients for reflection and transmission for a quasi-compression (qC) wave incident at the weld – fine grain interface from the weld.

Since both Sh and compression waves have good transmission properties at the interface the choice of wave modes must be dictated by other considerations. For instance, the Sh wave makes good use of the high corner reflectivity to detect defects at the far surface whereas compression waves are best utilised for defects away from the surface, in particular embedded cracks.

The usefulness of vertically polarised quasi-shear (qSv) waves is restricted to small angles of incidence. Figures A1.10-A1.11 and Figures A1.12-A1.13 show the situation for Sv waves incident from the fine grain side and qSv waves from the weld side respectively. The critical angle for the compression wave mode occurs at approximately 35° and at higher angles the energy balance is achieved by redistribution to other reflected and refracted wave modes. At angles of incidence higher than approximatively 58° it is the second quasi-shear wave mode, qSv(2), that is the dominant shear wave mode in weld, see Figure A1.11.

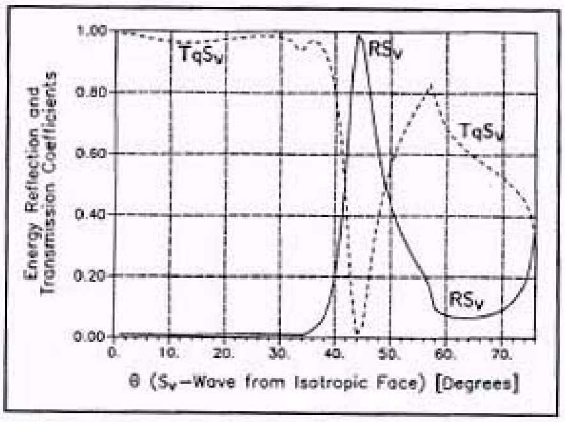


Figure A1.10 - Energy reflection and transmission coefficients for a vertically polarized shear (Sv) wave incident at the weld – fine grain interface from the fine grain base metal.

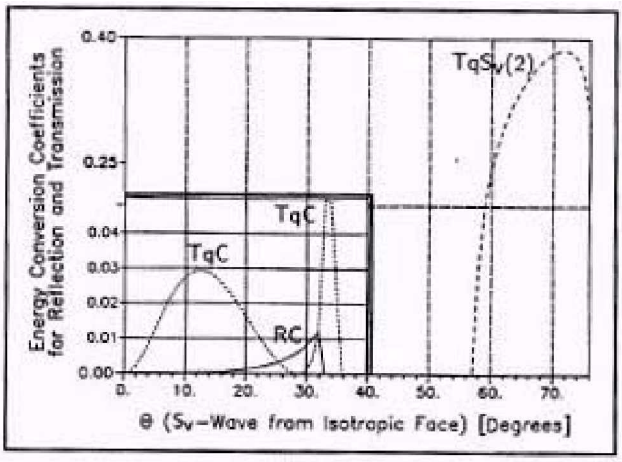


Figure A1.11 - Energy conversion coefficients for reflection and transmission of a vertically polarized shear (Sv) wave incident at the weld – fine grain interface from the fine grain base metal. (Note that the coefficients of the transmitted quasi-compression wave (TqC) and the reflected compression wave (RC) are on a separate scale)

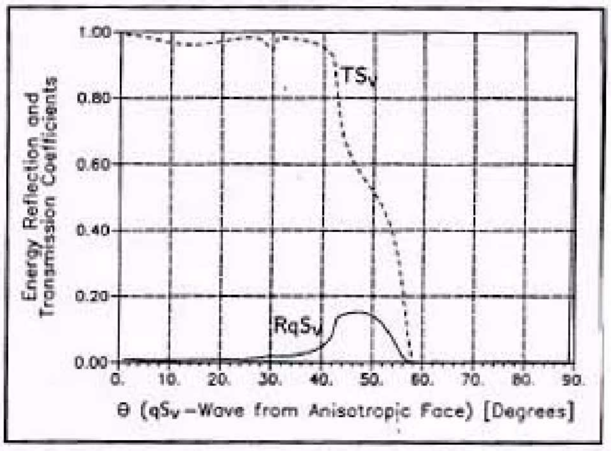


Figure A1.12 - Energy reflection and transmission coefficients for a vertically polarized quasi-shear (qSv) wave incident at the weld – fine grain interface from the weld.

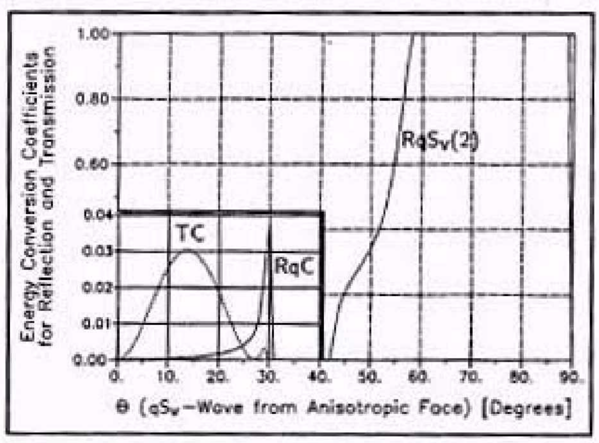


Figure A1.13 - Energy conversion coefficients for reflection and transmission of a vertically polarized quasi-shear (qSv) wave incident at the weld – fine grain interface from the weld. (Note that the coefficients of the transmitted compression wave (TC) and the reflected quasi-compression wave (RqC) are on a separate scale)

4.2 The ultrasonic probe's coupling layer

The special case of Sh waves is not treated here since they are not normally generated using liquid couplants and require electromagnetic techniques (see Appendix A5).

In addition to the energy transmission coefficients across the interface it is also important to know the efficiency with which energy is transmitted across the coupling layer between the perpex wedge of the probe and the weld surface. Figures A1.14 and A1.15 show the energy transmission coefficients for both refracted wave types which are similar to those for the case of a perpex-isotropic steel interface. Figure A1.14 shows that the second quasi-shear wave mode qSv(2), although present, is very weak and can be ignored during ultrasonic testing.

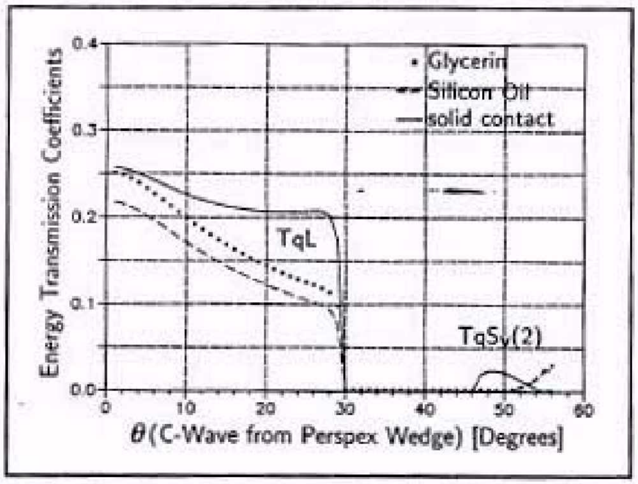


Figure A1.14 - Energy transmission coefficients of the quasi-compression (qC) wave generated in the weld at the coupling layer between the perpex wedge of the ultrasonic probe and the weld. Testing frequency: 2 MHz, solid contact and fluid contact. Thickness of the coupling layer in the case of fluid contact : 20 µm.

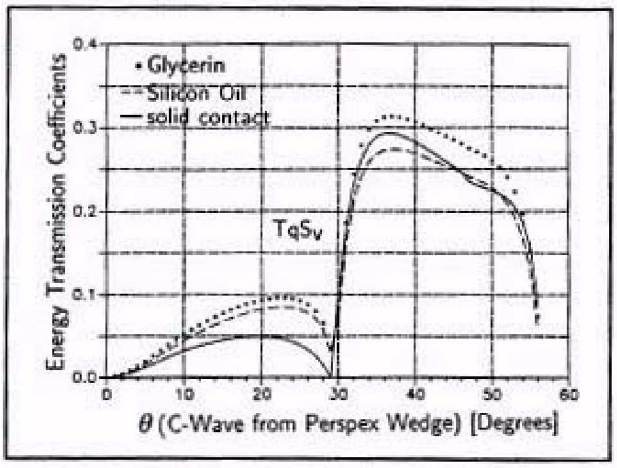


Figure A3.15 - Energy transmission coefficients of the quasi-shear (qSv) wave generated in the weld at the coupling layer between the perpex wedge of the ultrasonic probe and the weld. Testing frequency: 2 MHz, solid contact and fluid contact. Thickness of the coupling layer in the case of fluid contact : 20 µm.

Appendix A2

Effects of the microstructure on the ultrasound

Chapter 4 gives a brief explanation of some of the effects encountered by ultrasonic beams passing through anisotropic weld metal. This appendix, derived from the the similar in the « Handbook for the Ultrasonic Examination of Austenitic Clad Components » provides more theoreticam details of these effects for the readers interested in the subject.

A2.1 Features of columnar grained weld metal

This section defines the features of austenitic welds that are important to understand the behaviour of ultrasound in this material. It also defines the necessary assumptions that are made ti quantify the effects of grain structure on ultrasound propagation.

Acoustic anisotropy of austenitic weld metal is caused by the fact that the grains with cubic single crystal symmetry form an ordered columnar structure, similar to a fibre texture. One the three crystalllographic axis of the cubic crystal has approximately the same direction for all grains, whereas both other crystallographic axes are randomly distributed. The unidirectional fibre texture is said to be transversaly isotropic and therefore rotationally symmetrical.

The ultrasonic properties of the material are defined by elastic constants.

For a single cubic crystal such as a single grain of austenitic weld metal, there are only three independent elastic constants c11, c12, and c44.

For transversaly isotopic material such as the bulk of austenitic weld metal, there are five elastic constants c11, c12, c13, c33 and c44, all of wich can be derived from the single crystal elastic constants using the texture coefificients of the orientation distribution function for the columnar grain in the weld metal. Alternatively, they can be calculated from the phase velocity surface measured on austenitic weld metal. Thtoughout this handbook the following elastic stiffness constants derived from phase velocity measurements on pads of X 6 Cr Ni 18 11 weld metal are used :

c11= 2.4110 x 10exp11 N/m2
c12= 9.6916 x 10exp11 N/m2
c13= 1.3803 x 10exp11 N/m2
c33= 2.4012 x 10exp11 N/m2
c44= 1.1229 x 10exp11 N/m2

The precise value of each of the constants depends upon chemical composition of the material.

For many cases, the predictions of ultrasonic propagation through austenitic weld metal, such as ray tracing, are only midly sensitivr to small changes in the elastic constants. There are cases however , for instance the propagation in high angle beams in weld metal, where the predictions can be very sensitive to small changes in the constants.

To theoretically model the propagation of ultrasound in weld metal, it is assumed that :

- the ultrasound is a plane, monofrequent wave. This assumption is a fairly good model, since ultrasonic transducers has large dimensions as compared with the ultrasonic wavelength. Of course, effects of diffraction and mode conversionat the aperture edges of the ultrasonic transducers, e.g. generation of surface or creeping waves, are excluded by this assumption
- the columnar grains are normal to the surface, therefore they always lie in the plane of wave incidence. There are obviously exceptions to this, such as the overlaps between layers were the grain tilt may be very large.

Two types of columnar grain tilt may occur :

- the columnar grains may be tilted in the plane of wave incidence. This would change the sound veloocity.
- the columnar grains may be tilted from the plane of wave incidence. This would change the character of the wave mode and their energy flow would be no longer in the plane of sound propagation.

For strip caldding and for some weld metal, sound propagation is modelled to take place in the meridian plane of the columnar grain structure, i.e. containing the columnar grains and the incident ultrasonic beam, see fig. A2.1

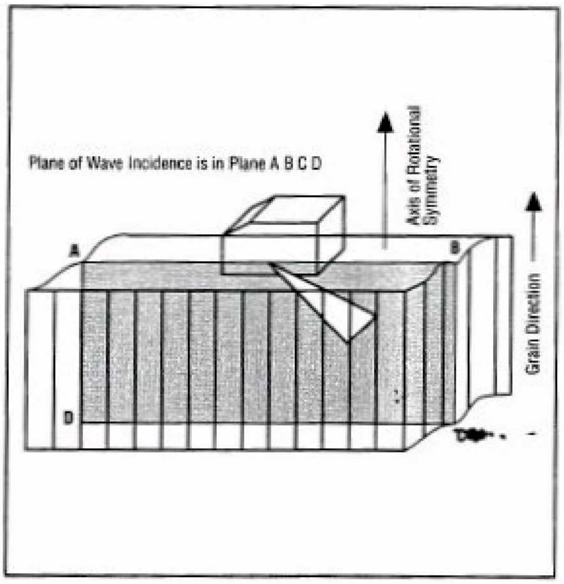


Fig.A2.1 Grain direction, plane of incidence and axis of rotational symmetry.

A2.2 The velocity surfaces

This section defines the group velocity and phase velocity surfaces in a more formal manner than the treatment given in chapter 4.

Imagine a small randomly polarized acoustically isotropic material, e.g. ferritic material, then the ultrasonic pulse emanating from this source would form a two sheeted spherical wave surface (see fig.2.2)

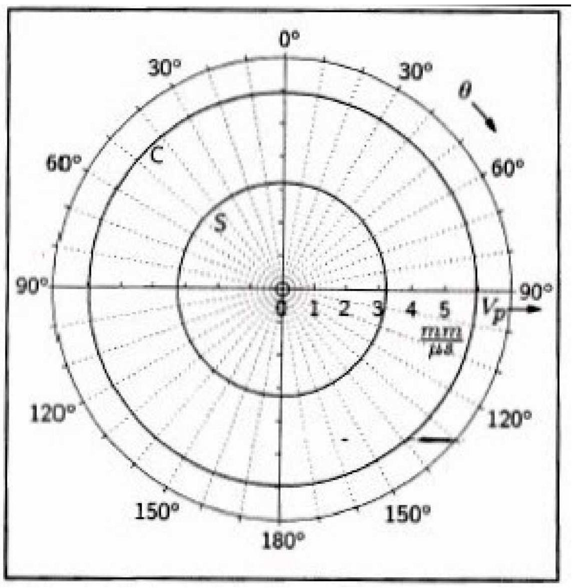


Fig. A2.2 Section of the two sheeted spherical phase velocity surface for ferritic steel

The outer surface represents the compression ©wave and the inner spere the shear (S) wave. These spheres are the loci of the phase velocities and they are sometimes referred as normal surfaces, or phase velocity surfaces.

There is an additional parameter, the group velocity (Vg), that needs to be defined in order to understand the propagationof ultrasound though anistropic materials. The group velocity is the velocity at which the energy propagates through a material and the direction of the group velocity is often referred to as the ray or beam direction. In isotropic materials, such as ferritic steel, the distinction between the phase velocity and the group velocity is not normally made, since the two velocities are the same numerically and in direction. However, as we will see later, this is not the case for anisotropic materials.

In acoustically anistropic materials, e.g. weld metal, the propagation behaviour of ultrasound is quite different. Generally, in such a material, there are three and only three wave mode, one compression and two shear waves modes which propagates, i.e. Vg in not in the plane of propagation.

Imagine again a small, randomlly polarized acoustic source now located within the acoustically anisotropic material. The ultrasonic pulse, emanating from this source would form the group velocity surface consisting of three sheets, e.g. fig A2.3

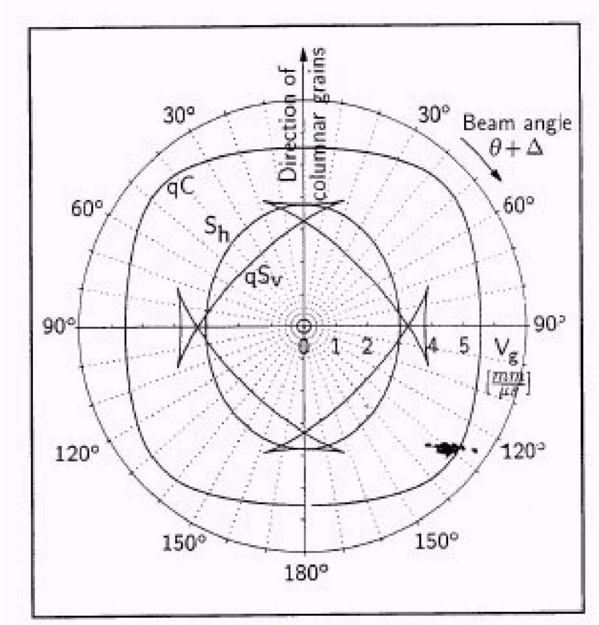


Fig.A2.3 – Meridian section of the three sheeted group velocity surface in transverse isotopic austenitic weld metal

The three sheets correspond to th three wave modes with different polarization. The group velocity surface is a plot of the group velocity Vg versus the energy flux direction. The group velocity surface, which is generally non sherical, represents the propagation of acoustic energy. It is the appropriate surface for Huygens' construction of wave propagation. The phase velocity surface shown in fig. A2.4 which is also non sherical in acoustically anisotropic material, is a plot of the phase velocity Vp versus the wave vector direction.

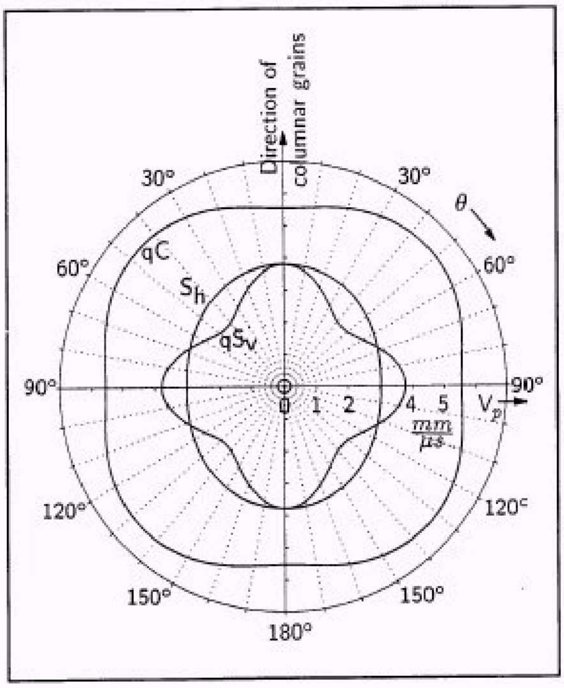


Fig.A2.4 – Meridian section of the three sheeted phase velocity surface in a transvers isotropic austenitic weld metal.

The phase velocity surface is not identical to the group velocity surface since the velocities of acoustic energy and wave fronts are different in size and direction. The energy flow direction is therefore skewed at an angle to the wave vector.

Because of the rotational symmetry of columnar grained austenitic weld metal, the phase- and group- velocities of all three modes, during propagation in the meridian plane, are independent of the polar angle. Their magnitude and direction depend only on the angle θ between the columnar grain axis and the wave vector and also on the plarisations. In the caseof austenitic weld metal shown in fig. A2.4, the phase velocity of quasi-compression (qC), horizontally polarized shear (Sh), and vertically polarized quasi-shear (qSv)waves could vary up to 20%, 30% and 50%, repectively.

During sound propagation in the meridian plane of transversaly isotropic austenitic weld metal theenergy flow of the three waves type is confined to the meridian plane. The waves are therefore said to be coplanar. If the columnar grainsnare tilted from the plane of wave propagation the energy flow of the three wave types is no longer in the plane of sound propagation. It is generally skewed from it : the sound propagation is sais to be non-coplanar.

A2.3 Polarisation

The particle displacement polarisation of acoustic waves in acoustically isotopic material material is known to be in the direction of propagation, i.e. in the direction of the wave vector, for the compression wave mode and transverse to the direction of propagation for the shear wave mode. This means that the shear wave mode can be arbitrarily polarized in so far as for its patricle displacement polarisation all directions tranversee to the direction of propagation are possible.

In acoustically anisotopic materials particles displacement polarisation are always mutually orthogonal, but in general that deviate from the direction of the wave vector for compression waves and the direction transverse to the wave vector for shear waves. The wave modes are mixed in the sense that each mode contains components of particle displacement, which are characteristic for the other wave modes. Therefore, these wave modes are no longer pure compression or pure shear modes.

If the displacements have predominantly compression or shear wave character, they are called quasi-compression or quasi-shear, respectively.

During sound propagation in the meridian plane of austenitic weld metal, a pure shear (Sh), a quasi-shear (qSh) and a qusi-compression (qC) wave made exist (see fig. A2.5).

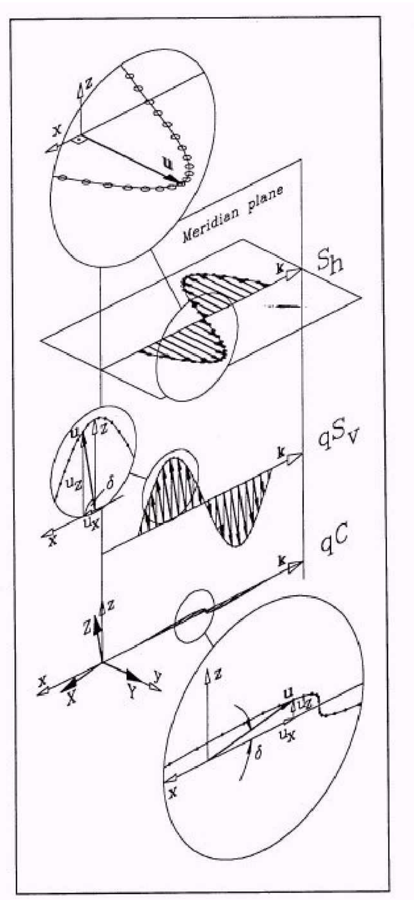


Fig.A2.5 – Schematic illustration of polarisation (represented by particle displacementu) and deviation δ of polarisation during sound propagation in the meridian plane of weld metal.

The pure shear wave is polarized perpendicular to the plane of wave incidence and therefore always polarized perpendicular to the columnar grain axis.This polarisationis designated « horizontally polarized shear ». The polarisation direction in both quasi waves qC and qSv are in the plane of columnar grains, i.e. the meridian plane, which is also the plane of propagation. In that plane, the direction of polarisation in dependent on the angle θ between the columnar grain axis and the wave vector (see fig.A2.6)

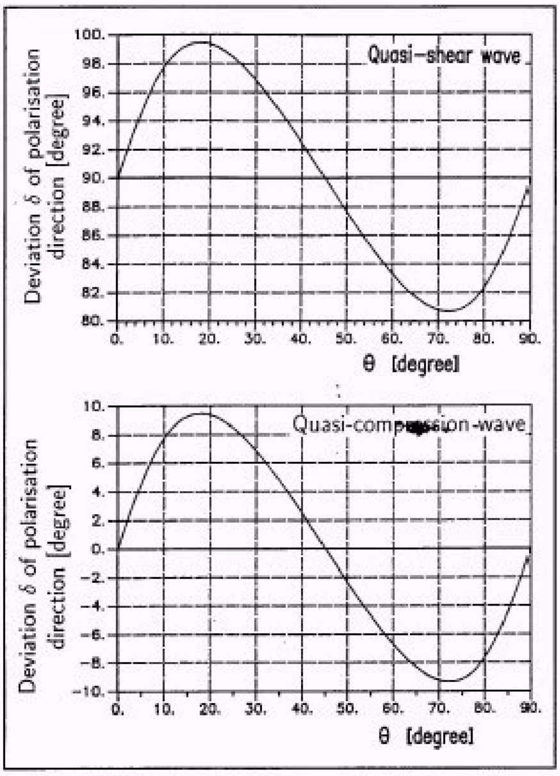


Fig.A2.6 – Deviation of polarization of quasi-compression waves and quasi-shear waves versus the angle of incidence during propagation in the meridian plane of austenitic weld metal.

This particle displacement polarisation deviates up to 10° from the direction of pure wave polarisation. Only in the direction θ = 0°, 45° and 90°, the wave modes are pure. During propagation along the columnar grain axis, the shear waves have the same velocity and can be arbitrarily polarized as in the isotropic ferritic material.

If the columnar grains do not lie in the plane of sound propagation, the characteristics of the wave modes will be changed. In this case the particle displacement polarizion for each wave are uniquely determined by the direction of the wave propagation with respect to the crystallographic axes.

Even in the case where the columnar grains are tilted from the plane of wave propagation, there is always a pure shear wave with polarization perpendicular to the wave vector, while the other wave modes have the « quasi »-character discussed above . But the particle displacement polarisations of all three wave modes then are neither in the planeof sound propagation, nor are they in the plane perpendicular to it. Therefore, the character of the shear wave being « vertically » or « horizontally » polarized during sound propagation in the meridian plane is not maintained. This is the reason why generally all three wave modes couple at boundaries. All wave modes are subject to mode conversion in polycrystalline material, except where the propagation takes place in the meridian plane.

A2.4 Beam Skewing

Fig. A2.7 indicates the effects to be expected when a source of arbitrary polarisation and having dimensions large compared to the wave length, such as an ultrasonic probe, is applied to the surface of an anisotropic medium.

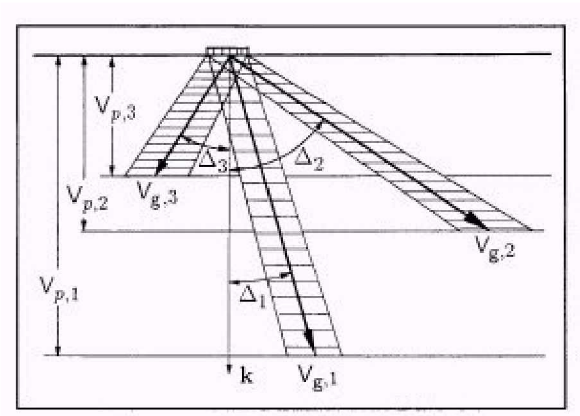


Fig.A2.7 – Ultrasonic beams in an anisotropic medium when radiated from a finite arbitrarily polarized source. The lines parrallel to the excited surface represent the planes which each type of vibration reaches per unit of time, the distances between source and these lines correspond to the three phase velocities, respectively, for wave vector k

The wave vector k is normal to the surface. The arbitrarily oscillary displacement of the ultrasonic source will be resolved int three mutually orthogonal polarized acoustic beams or acoustic energy fluxes. Each beam has an energy flux, propagating with group velocity Vg, wich is skewed at an angle Δ to the wave vector k. The wave fronts travel along the direction of the wave vector K with phase velocities Vp. The same effects, with adequate changes, are to be observed if the incidence of the wave fronts is tilted.
Phase velocity Vp and group velocity Vg are related by :

Vp = Vg cos Δ

Since the wave fronts are perpendicular to Vp and the end of the Vg vector is a point on the groupvelocity surface, fig.A2.8 shows how the above relationship impies that the wave vector is always perpendicular to the group velocity surface. This in turn means that each portion of the group velocity surface corresponds to the wave front for a planewave with energy travelling in that direction. From the above arguments it can be seen that the group velocity surface can be constructed from the enveloppe of the planes perpendicular to Vp.

Conversely the phase velocity surface can be constructed by tracing the pedal points of the tangent planes of the group velocity surface (see fig.A2.8). The pedal points are thegeometrical positions where a vector from the origin is perpendicular to the tangent plane. This vector is the phase velocity Vp, the end of which is a point on the phase velocity surface. So the phase velocity surface can be said to be the pedal surface of the group velocity surface. There are useful relationship since they means that either of these surfaces may be constructed from the other withou knowing the skewing angle.

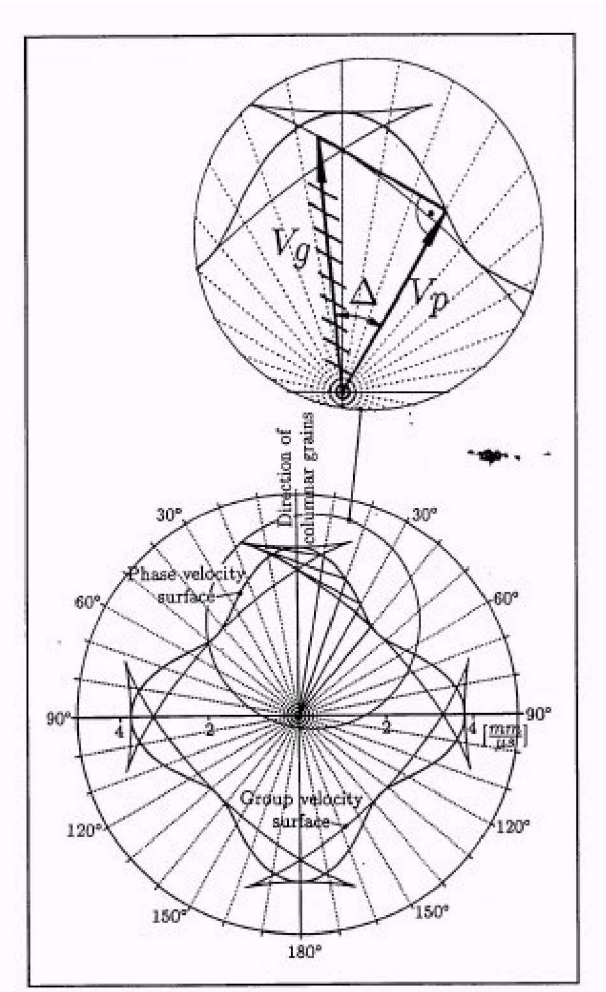


Fig.A2.8 – Relationship betweenphase velocity surface and group velocity surface, demonstated for the quasi)shear wave in the meridian plane of austenitic weld metal : group velocity surface as enveloppe of the phase velocity surface and phase velocity surface as pedal surface of the group velocity surface.

Appendix 3

Slowness surfaces

A3.1 Introduction

The slowness surface is a tool for describing the propagation of ultrasound at interfaces. In order to become familiar with this concept, the physics of ultrasonic waves have to be studied first. At least the following parameters should be known: the velocity of ultrasonic waves, the direction of energy propagation and the beam skewing depending of the microstructure of the material (isotopic ferritic steel or anisotropic austenitic base metal and weld metal). This appaendix shall explain the use of the slowness surface diagrams based on two simple examples.

A3.2 Definitions

Wave normal direction	Propagation direction of the wave
Compression wave	Particle motion parallel to the wave normal direction
Vertically polarized shear wave Sv	Particle motion perpendicualar to the wave normal direction
Horizontally polarized shear wave Sh	Particle motion perpendicular to the wave normal direction
Phase velocity Vp	The velocity of a point of constant phase on the wave front. It is measured at right angles to the wave front
Phase velocity surface	Plot of the size of the phase velocity versus its direction in a polar graph.
Slowness surface	Plot of 1/Vp as a function of the wave normal direction
Energy of group velocity Vg	Velocity of the energy flow which is measured in the direction of sound beam
Angle θ	The angle between the wave normal and the columnar grain

Angle Δ	Skewing angle of energy flow (deviation in diection of Vg respective to Vp)

A3.3 Examples of slowness surfaces

A3.3.1 Isotropic case

In isotropic material, the slowness surface is a two-sheeted surface of spherical shape. For ferritic steel, it consists of two spheres with radii of 1/5.95 µS/mm for compression waves and 1/ 3.23 µS/mm for shear waves (fig.A3.1 lower part). The slowness surface for compression waves in perspex is a sphere of a radius of 1/ 2.73 µS/mm as shown in the upper part of Fig A3.1. The graphs are a section in the plane of incidence and they allow us to construct Snell's law.

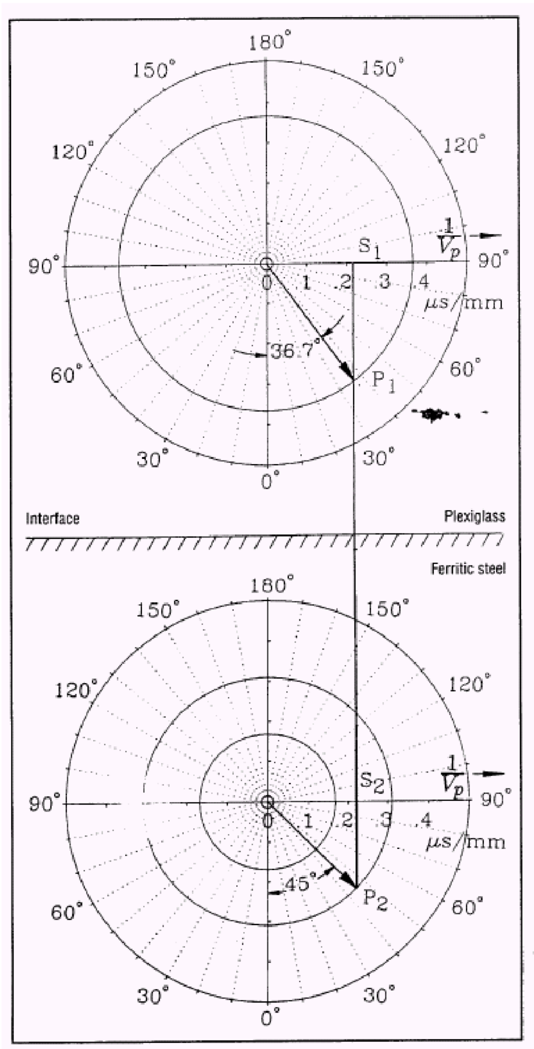


Fig.A3.1 – Slowness surfaces for ferritic steel and plexiglass to determine the *refraction angle at the interface*

A 45° shear wave probe (for examination of ferritic steel) has a perpex angle of 36.7° as given by the Snell's law :

$$\text{Sin } 45°/3.23 = \text{Sin } 36.7°/2.73 \quad (1)$$

As P1 is on the slowness surface the line

$$OP1= 1/Vc \text{ with } Vc= Vp = Vg \text{ and} \quad (2)$$
$$OS1= OP1 \sin 36.7° = \sin 36.7°/Vc \quad (3)$$

The expression on the right side of the equation (3) represents one side of Snell's law (equation 1) whereas the corresponding expression for OS2 equals the other side of Snell's law. From this, we can conclude that OS1=OS2 which is aquivalent to equalising the tangential component of the slowness 1/Vp in perspex and steel. Based on this knowledge, we are now able to determine the refraction angle at the interface perspex-ferritic steel carrying out the following steps :

- Draw the beam angle of the compression wave in the slowness surface of the perspex line (line OP1)
- Draw a perpendicular line on the interface through point P1
- Mark the point of intersection of this line with the slowness surface of the shear wave in ferritic steel as P2
- The line OP2 gives the direction of the refracted sound beam in ferritic steel

A3.3.2 Anisotropic case

In anisotropic material, the slowness surface is a three-sheeted surface on non-sherical shape corresponding to one compression and two shear wave modes.
Figure A3.2 shows the slowness surface for compression ©, Sv and Sh waves in columnar grained austenitic steel. By definition, the direction of the phase velocity is given by a line through the origin. The direction of the group velocity is different in anistopic material, it is given by a line perpendicula to the tangent of the curve. The angle between the group and the phase velocity is the skewing angle Δ/

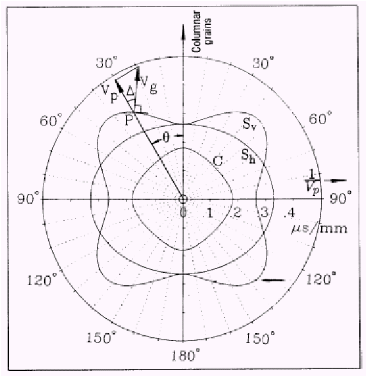


Fig. A3.2 – Slowness surface for both shear waves and compression waves in anisotropic material

Figure A3.3 gives an example for a 45° shear waves probe. It describes how sound propagation is influenced at the interface between fine grain austenitic steel and the austenitic weld metal having columnar grains perpendicular to the surface. The vertical through pont P1 results in point P2 giving the direction of the phase velocity (34°) in the weld metal. The group velocity direction (perpendicular to the tangent at P2) is only about 7°. Therefore the beam is heavily skewed in the weld metal.

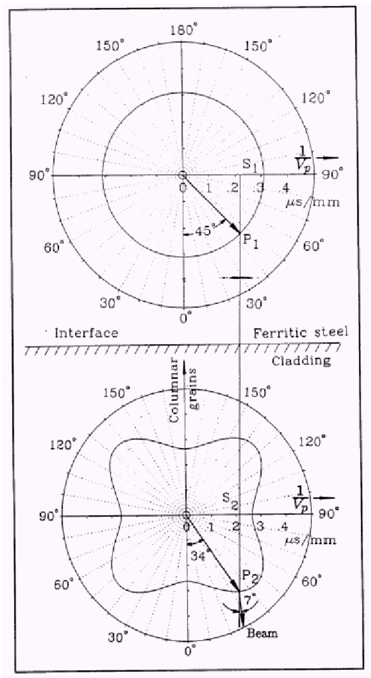


Fig. A3.3 – Slowness surfaces for fine grain austenitic material and weld metal todetermine the refraction at the interface.

These two examples given above are showing the principles of using the slowness surface concept.
The concept can also be used to explain the critical angles or the phenomenon of beam splitting in anisotropic material.

Appendix 4

Phased Array technique

The Phased Array Technology allows generation of an ultrasonic beam with the possibility of setting the beam parameters such as angle, focal distance and focal point size through software.

The capability of dynamically changing the properties and parameters of the probe opens a series of new possibilities over conventional UT technologies. It is possible to quickly vary the angle of the beam to scan a part without moving the probe itself, allowing multi-angle inspection of complex geometry from a single point. Phased Array technology also allows the replacement of multiple probes by a single phased array transducer. Inspecting a part with a variable angle beam also ensures detection no matter what the angle of the defect with optimal signal-to-noise ratio.

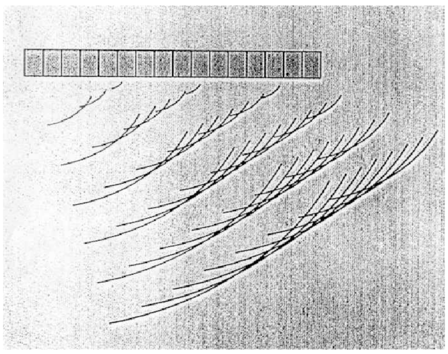
A Phased Array probe is typically a one or two-dimensional array of small transducer elements. To control the beam characteristics, the excitation pulse is applied at different times to the various elements of the probe. Different Phased Array probe configurations are for example rho-theta, circular, matrix and linear.

Beam angle control

Simultaneous pulsing of all elements of a linear transducer array produces a resulting wavefront, which is perpendicular to the transducer plane. Phased array system allow the pulsing of the various elements in a sequential manner, with a small and precisely controlled time delay from one element to the next. The resulting wavefront propagates at an angle (figure 1) which is controlled by the applied delay.

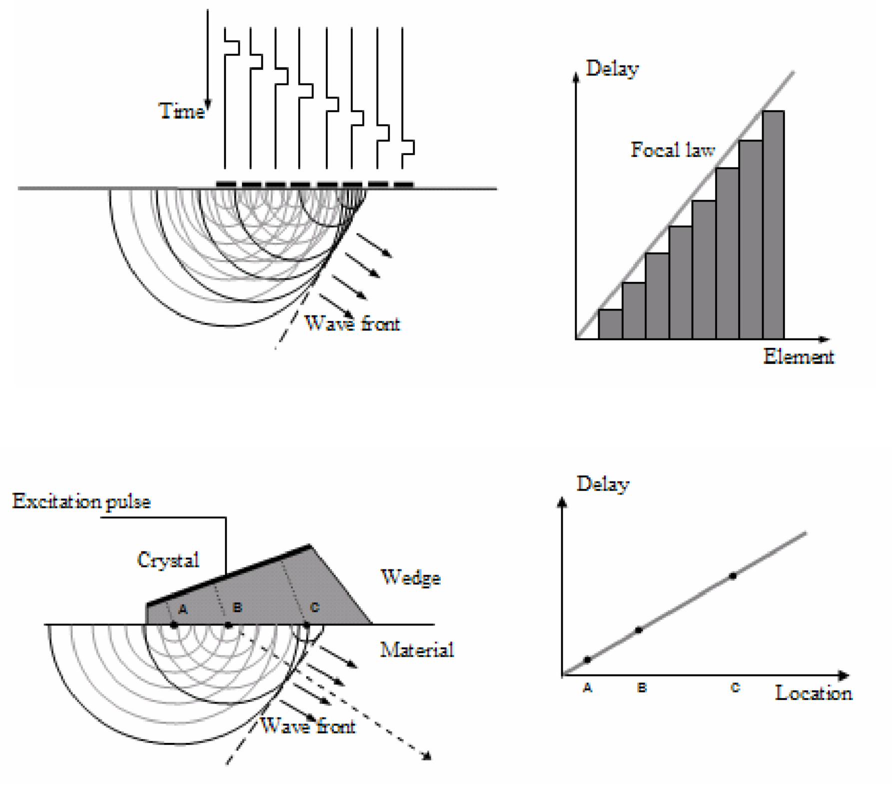
A similar principle is also applied to the received signal. Echoes from a given point in the material hit the various transducer elements with a computable relative delay. This delay is dependent on the distance of the emitting point (focal point) to the various transducer elements. The signals received at each transducer element are time synchronised by the phased array system prior to summing up the various responses.

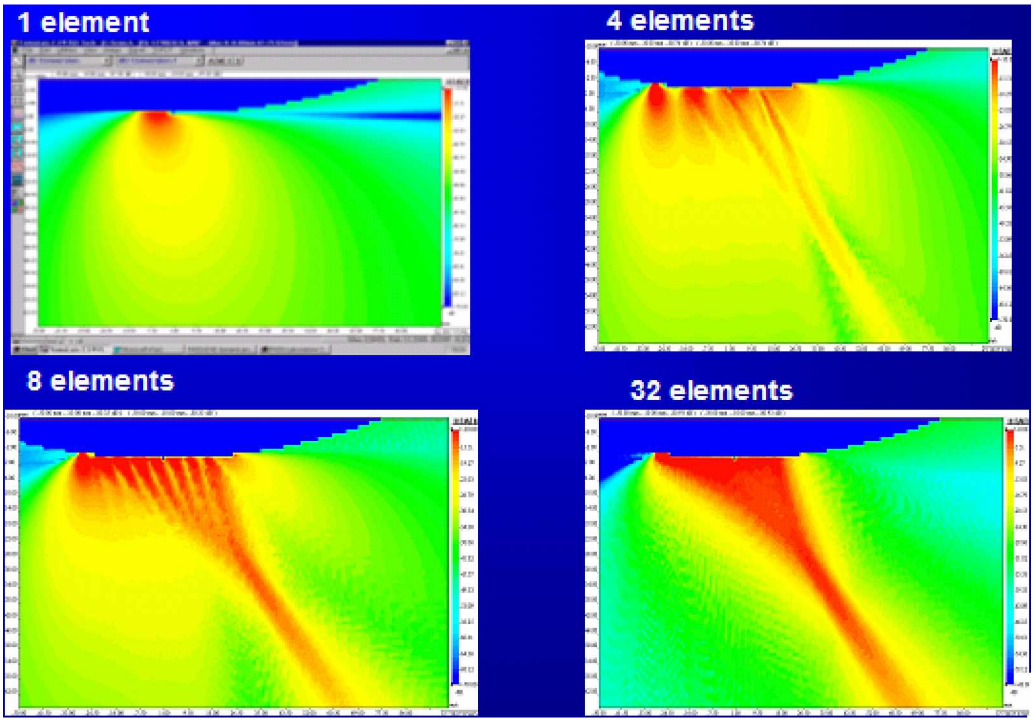
In pulse echo mode, the pulsing delays applied to the various transducer elements are the same as those applied to the received signals. The timing definition for pulsing and receiving associated with a specific angle and focal length is called a *focal law*.



9.1.1.1 Beam focusing

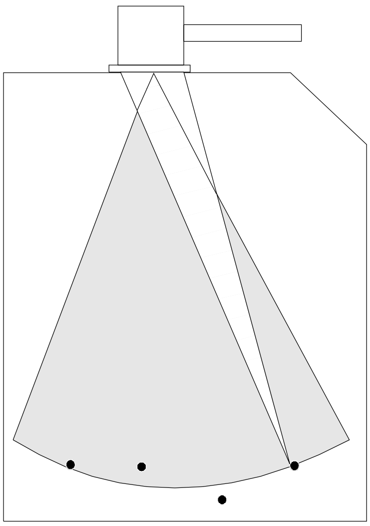
Beam focusing can also be achieved in a similar fashion. When the central elements of the transducer array are fired with longer delays compared to that of the lateral elements, each of the individual wavefront can be made to arrive in phase at the desired focal point (figure 2). The resulting ultrasonic beam is effectively focussed at that point.





9.1.1.2 Electronic scanning

A phased array system can produce a beam displacement along a transducer array (figure 3) using a multiplexer. In the same manner, beam rotation may be achieved when used with a circular transducer array.



APPENDIX 5

Electromagnetic Acoustic Transducers for SH waves

1. Introduction

Today practically all ultrasonic inspections are performed with compression waves and vertically polarized shear SV waves generated by transducers containing piezoelectric crystals. The transducer are mechanically coupled to the work piece by a liquid or gel so they can be scanned across surfaces. Recent theory and experimental work has shown that there are many advantages to using the uncommon wave mode horizontally polarized shear SH waves for the ultrasonic examination of fusion welded austenitic materials, and the main advantages are listed in Chapter... In principle SH waves can be generated with piezoelectric transducers, but highly viscous couplants are necessary which makes scanning extremely difficult if not impossible. SH waves can however be generated by electromagnetic acoustic transducers (EMATs).

This Appendix briefly introduces SH EMAT technology since this type of transducer has started to be used for the ultrasonic inspection of fusion welded austenitic materials and it is important to understand how they function and some of their limitations. It must be emphasised however that at the time of completing this handbook (......) SH EMAT transducers were build only in small numbers of pieces, although some convincing demonstrations of their potential value have been reported. Furtermore for some specific applications the EMAT SH wave technique has been qualified.

2. Physical Principles

EMATs generate ultrasonic waves directly in the surface of a component by either the Lorentz force or the magnetostrictive effect, depending on the magnetic properties of the component under test. The physical principle of EMAT operation by Lorentz forces is shown in Fig. 1. Suppose that a wire is arranged adjacent to a metal surface and driven by an electrical current at the desired ultrasonic frequency. Eddy currents with the current density J_ω are induced at the metal surface and, if a static magnetic bias induction B_o is also present, the eddy currents experience periodic Lorentz forces F_L given by the vector product:

$$F_L \approx J_\omega \times B_o \qquad (1)$$

The Lorentz forces on the eddy currents are transmitted to the solid by collisions with the lattice or other microscopic processes. These forces on the solid are alternating at the frequency of the driving current and act as a source of ultrasonic waves. The electric current is normally generated by a radio frequency (RF) coil (eddy current probe) energised with pulsed current so that the ultrasonic wave is also pulsed. The process of electromagnetic acoustic excitation in solids by Lorentz forces is in many ways similar to that which creates motion in an electrical motor. Reciprocal mechanisms also exists whereby ultrasonic waves can be detected, a process analogous to operation of an electrical generator.

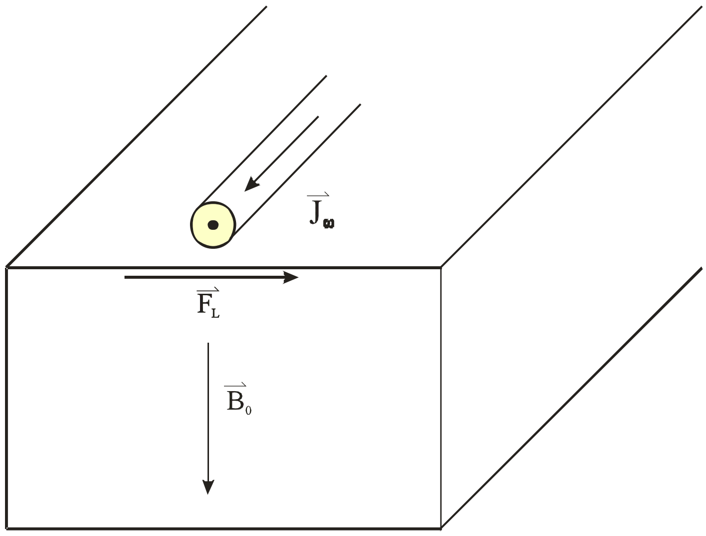
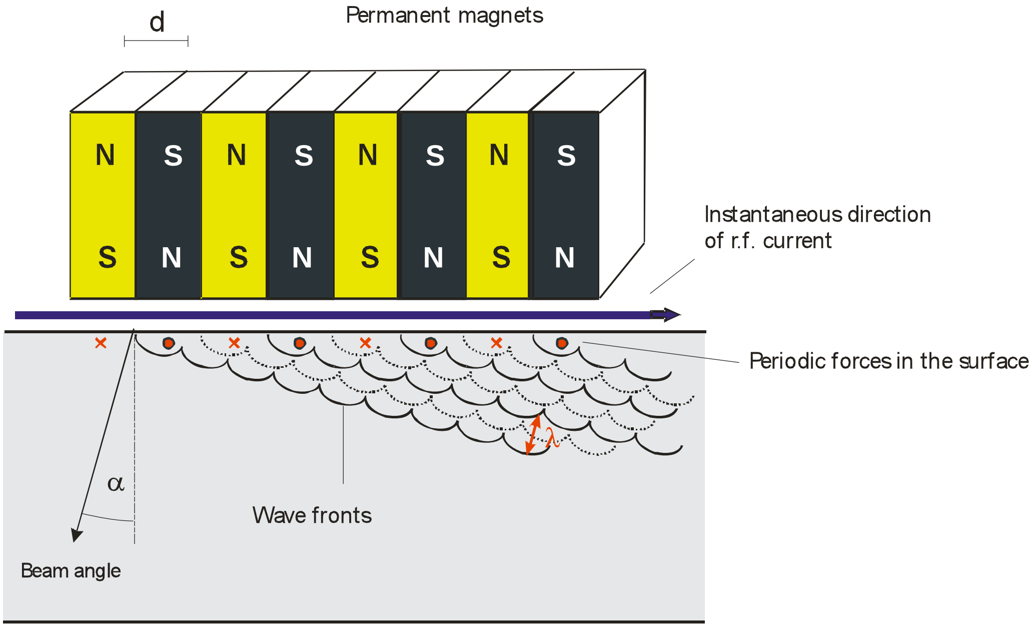


Fig. 1 Principle of Electromagnetic Excitation by Lorentz Forces

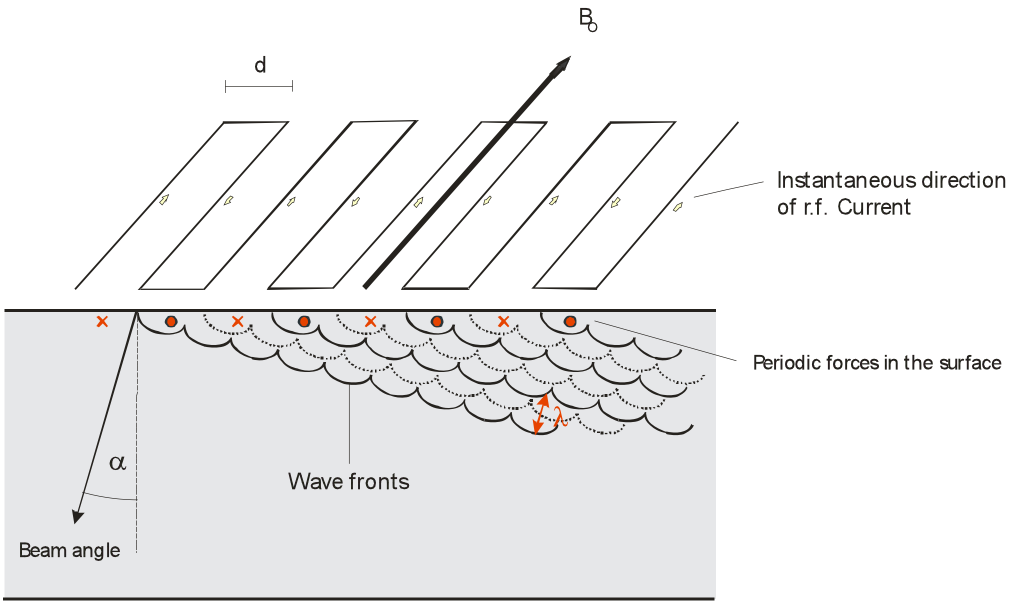
In magnetic materials ultrasonic waves can be generated by the magnetostrictive process by the application of a magnetic field combined with the pulsed field from a RF coil. For the generation of SH waves the direction of the magnetic bias field is parallel with the direction of the eddy currents and these are at right angles to the direction of propagation for the ultrasonic wave.

3. General properties of EMATs for the angle incidence

To produce ultrasonic beams with a high degree of directionality and intensity with EMATs it is necessary first to generate spatially periodic forces in an electrically conducting surface as shown in Figure 2.



(a) SH-waves Generated by the Lorentz Force



(b) SH-waves Generated by the Magnetostrictive Effect

Fig. 2 : The generation of SH ultrasonic waves by EMATs

Figure 2(a) shows an arrangement of permanent magnets with alternating fields which when combined with eddy currents induced in the surface by the RF coil generates transverse periodic forces in the surface by the Lorentz force. By constructive interference these forces combine to produce an SH wave with a beam angle α given by:

$$\alpha = \arcsin(\lambda/2d) \qquad (2)$$

where λ is the wavelength of the generated ultrasonic wave and d the spacing between elements (magnets). For constructive interference to occur 2d must be equal to or less than λ and the pulse length applied to the RF coil should be greater than m/2 cycles, where m is the number of elements (magnets) in the EMAT. The beam angle is controlled by varying the frequency of the RF current pulse and this is given by a simple re-arrangement of equation (2)

$$\alpha = \arcsin(ct/2df) \qquad (3)$$

where ct is the sound velocity of SH waves and f the frequency of the current pulse.

Fig. 3 gives the beam angle of an EMAT probe as a function of the frequency f for different element spacings d for austenitic steel where ct = 3.14 mm/µs.

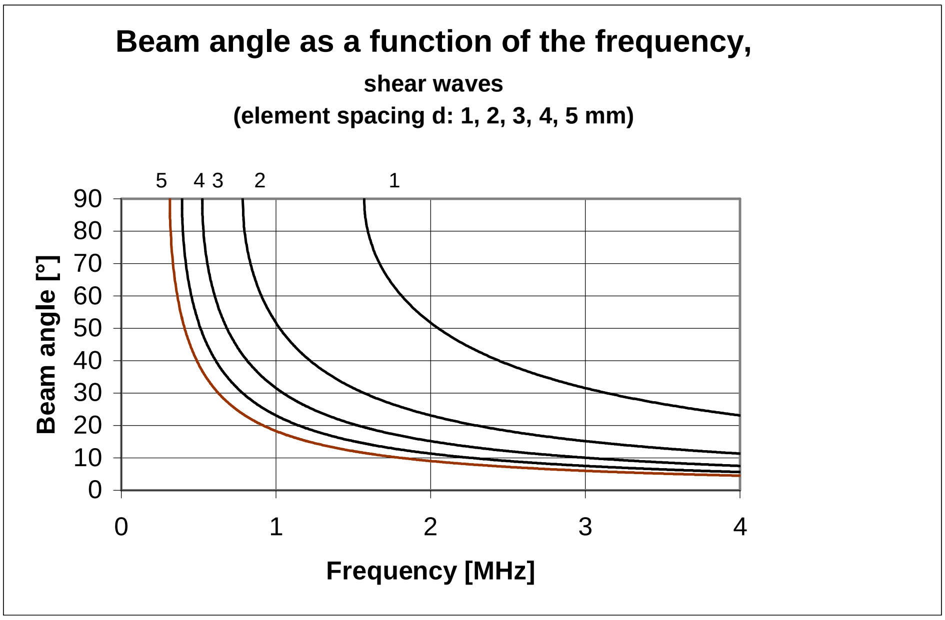


Fig 3: SH wave beam angle for an EMAT probe as shown in Fig 2 assuming $c_t = 3.14$ mm/µs

Fig. 2(b) shows a meander RF coil in which the direction of current flow in each line element alternates and the dynamic magnetic fields of each line element modulate the main bias magnetic induction Bo which is parallel to the surface. The periodic forces in the surface are produced by the magnetostriction effect due to superposition of the static magnetic field with the dynamic magnetic fields generated by the current in each line element of the RF coil. By constructive interference the wavelets produced by the periodic forces combine in the same way as in Fig. 2(a) to generate an SH wave with a beam angle given by equation (2) and a long pulse length. In each case if one large RF coil is used the EMAT produces a bidirectional radiation characteristic.

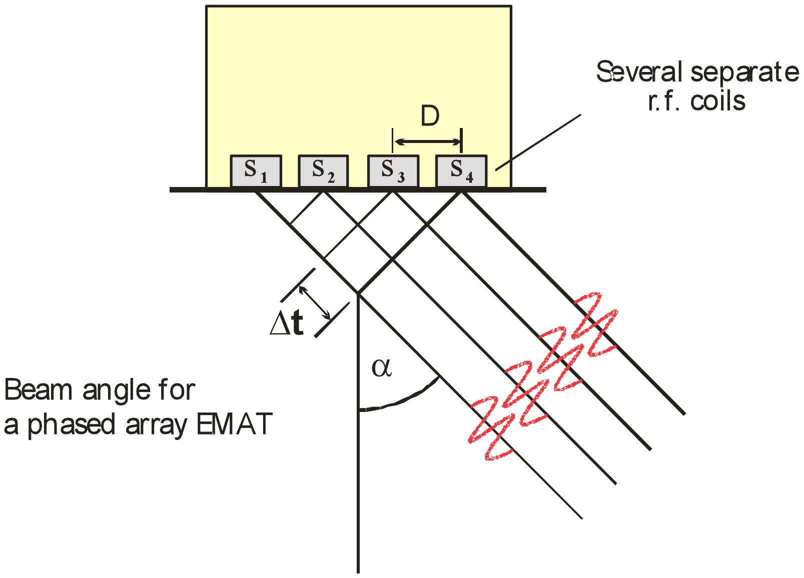


Fig.4: Changing the beam angle by the time delay

If instead of one large RF coil several smaller coils are used as shown in Fig. 4 and these are energised sequentially each by a separate power stage like a phased array with a time delay Δt between each current pulse an SH wave with a wave front is produced with a beam angle α given by:

$$\alpha = \arcsin (c_t \Delta t/D) \qquad (4)$$

Phased array technology can also be applied to the Lorentz Force EMAT. The advantage of the phased array approach is that there are no limitations to pulse length and a ratio of forward to backward radiation greater than one can be achieved.

EMATs do not require any mechanical coupling between the transducer and the component under test. It is however necessary for the RF coil and with restrictions also for the magnet to be close to the surface of the component since eddy current lift off losses and losses due to a larger air gap of the magnetic circuit can be large.

4. Probe configurations

4.1 Electromagnet probes

Fig. 5 shows a magnetostrictive SH wave EMAT for ferromagnetic materials. The magnetic bias field is produced by a U shaped electromagnet energised with 50 or 60 Hz alternating current to enable the EMAT to be scanned over a ferritic surface.

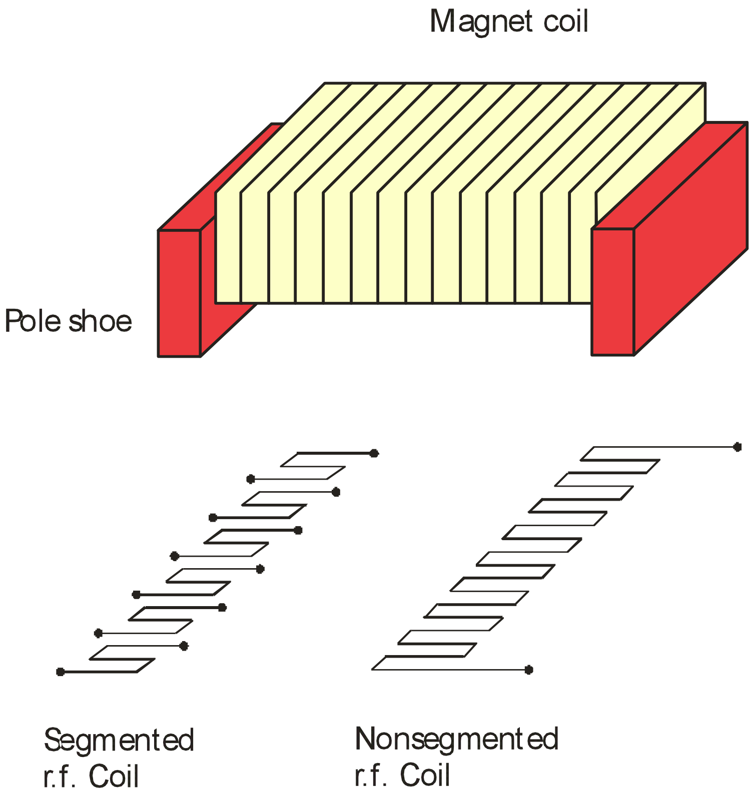


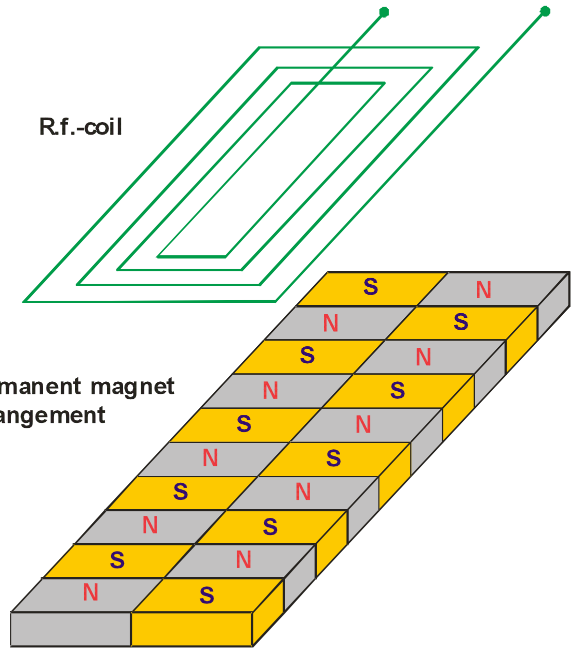
Fig. 5 : EMAT probe for SH-waves with Electromagnet

The RF coil is one Meander coil or is divided into several segments and these are driven as a phased array as described for Fig. 4 to generate a SH wave which propagates in the direction perpendicular to the magnetic bias field.

4.2 Permanent magnet probes

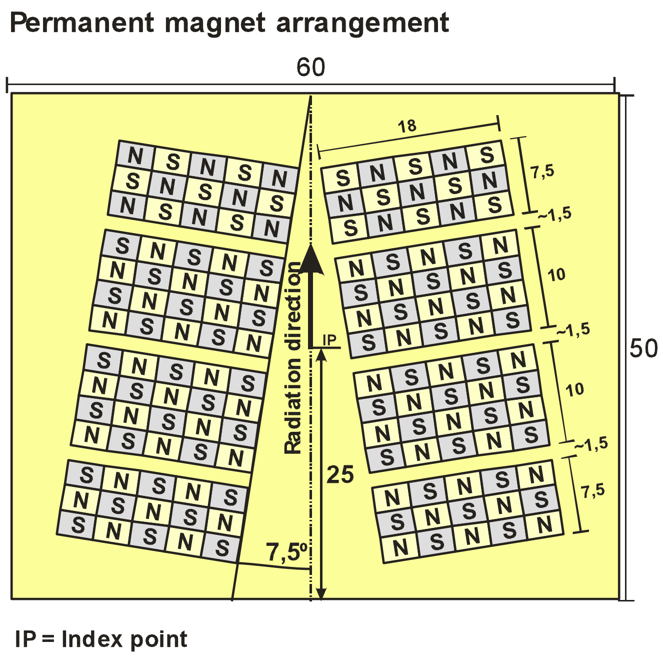
In non ferromagnetic or weakly ferromagnetic materials ultrasonic waves are excited by the Lorentz force. Fig. 6(a) shows an arrangement of permanent magnets and RF coils for generating SH waves as described earlier for Fig. 2(a).

Top view on the bottom side



(a) Nonsegmented EMAT with Permanent Magnets

Top view on the bottom side, r.f.-coils are not shown



(b) Segmented EMAT with Permanent magnets, Phased Array probe

Fig. 6: EMAT probes for SH-waves with Permanent Magnets

At least two rows of oppositely polarized magnets and a rectangular coil are required to generate an ultrasonic wave. These permanent magnet probes often are constructed as phased array transducers with multiple segments as it is shown in Fig. 6 (b)

5. Practical Points About EMAT probes

Separate transmitter (T) and receiver (R) EMATs are normally used to avoid a long dead time following the T pulse. The R and T are normally arranged in a V formation to achieve pseudo focusing.

At the time of writing the handbook the following data gives a rough idea of the performance that can be achieved.

- Operating frequency range for SH wave EMATs is typically 0.5MHz to 1.8 MHz.
- The range of beam angles which can be achieved in any type of steel is 20° to 90°.
- Beam spreads of less than 10° can be achieved in the plane of incidence for beam angles smaller than 70° and perpendicular to the plane of incidence.
- For beam angles between 70° and 90° the beam spread in the plane of incidence is typically 15° to 20°
- For phased array transducers the ratio of the forward to backward radiation is typically in the range between 30 to 40 dB.
- A dynamic range of typically 35 dB can usually be achieved in austenitic steel. This may be enhenced to 45 dB when applied to surfaces containing δ ferrite.

APPENDIX 6

Typical techniques for Measuring Attenuation

Compression Wave Measurements

Probe

0º single crystal compression wave probe of the same frequency as the angled compression wave probes to be used for subsequent weld inspection.

Technique 1

The probe should be positioned on the parent material to be measured and two back wall echoes at a distance ratio 2:1 selected. (The first echo should be at least three near fields from the probe). When comparing the attenuation of different components (e.g. test piece and production parent material) the same back wall echoes should be used.
The echo height difference S (in dB) and the range difference T (in mm) between the two selected echoes are recorded. Since the back wall echo falls by 6dB for every doubling of the range (in the absence of attenuation associated with grain structure) the attenuation factor A (in dB) can be calculated from the formula:

$A= (S\text{-}6)/2T$

Measurements should be made on the parent material on both sides of the weld at a sufficient distance from the HAZ and any geometric impediments such as a counter bore. The more measurements made around or along a component, the more reliable the information on attenuation. As a minimum, it is recommended that measurements be made at three equi-distant points around/along the component, with the maximum distance between measuring points ±300mm.

Results

- Material exhibiting low attenuation is readily inspectable (typically ±0.02dB/mm at 2MHz).
- Material exhibiting medium attenuation should not be inspected with frequencies >2MHz (typically >0.02dB/mm, ±0.05dB/mm at 2MHz).
- Material exhibiting high attenuation may require frequencies <2MHz (typically >0.05dB/mm at 2MHz).

Technique 2

Attenuation measurements made in accordance with Technique 1 are often inconsistent. Wide variations in results can occur by slight changes in probe characteristics, or by selection of a different pair of back wall echoes. A more realistic and reliable technique involves counting the total number of back wall echoes, which can be resolved.

Measurements should be made on the parent material on both sides of the weld at a sufficient distance from the HAZ and any geometric impediments such as a counter bore. The more measurements made around or along a component, the more reliable the information on attenuation. As a minimum, it is recommended that measurements be made at three equi-distant points around/along the component, with the maximum distance between measuring points ±300mm.

Results

The number of back wall echoes achievable depends on the material thickness. Note that transmission losses at the near and far surface will have a greater effect on thinner, rather than thicker, material.

As an example, 40mm thick material measured with a 2MHz probe:

Low attenuation: >10 BWEs

Medium attenuation: 5 -10 BWEs

High attenuation: <5 BWEs

Shear Wave Measurements

Shear wave attenuation measurements are recommended whenever shear wave inspection is required.

9.1.1.3 Probes

Two 45° shear wave probes of size and frequency equivalent to the shear wave probes to be used for subsequent weld inspection.

Technique

The probes should be positioned on the parent material in pitch and catch formation and two signals at a distance ratio 2:1 selected. (The first signal should be at least three near fields from the probe). When comparing the attenuation of different components (e.g. test piece and production parent material) the same numbers of skip multiples should be used.
The signal height difference S (in dB) and the range difference T (in mm) between the two selected signals are recorded. Since the signal falls by 6dB for every doubling of the range (in the absence of attenuation associated with grain structure) the attenuation factor A (in dB) can be calculated from the formula:

$A = (S-6)/2T$

Measurements should be made on the parent material on both sides of the weld at a sufficient distance from the HAZ and any geometric impediments such as a counterbore. The more measurements made around or along a component, the more reliable the information on attenuation. As a minimum, it is recommended that measurements be made at three equi-distant points around/along the component, with the maximum distance between measuring points ±300mm.

Results

Material exhibiting low attenuation at ±0.02dB/mm at 2MHz is readily inspectable.

Material exhibiting medium attenuation >0.02dB/mm, ±0.05dB/mm at 2MHz should not be inspected with frequencies >2MHz.

Material exhibiting high attenuation >0.05dB/mm at 2MHz may require frequencies <2MHz.

5.2.3 Grain Size

Whenever it is known that ultrasonic examination through parent material will be required it is advisable that either attenuation limits, or a grain size limit, is specified to the supplier.

ASTM average grain size 5 (nominal diameter 65µm, average 248 grains/mm^2) or smaller grain size should be readily inspectable.

ASTM average grain size 3 and 4 (nominal diameter 90µm, average 124 grains/mm^2) should be inspected with compression wave frequencies no higher than 2MHz.

ASTM average grain sizes greater than 3 (nominal diameter 125µm, average 62 grains/mm^2) may require compression wave frequencies between 0.5-1MHz, although grain sizes ±1 may not be inspectable.