

Handbook on the Ultrasonic Examination of Austenitic Welds

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Handbook On the Ultrasonic Examination of Austenitic Welds

Compiled by

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and Control of Welds

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

For a definition of many of the terms used and further background information on the subject of this handbook, readers are referred to the existing IIW-publications listed below:

- (1) *List of Terms Used in Ultrasonic Testing* of the International Institute of Welding, 1967.
- (2) *Handbook on the Ultrasonic Examination of Welds* of the International Institute of Welding, 1977.
- (3) "Considerations on Ultrasonic Testing of Austenitic Weld Joints" *Welding in the World*, Vol 20 (1982), No 5/6, pp. 99-108.
- (4) "Geometrical defects in arc welded joints in steel materials — Classes of requirements" *Welding in the World*, Vol 22 (1984), No 1/2, pp. 34-52.

This Handbook has been produced by the Working Group Ultrasonic Testing of Austenitic Welds of the IIW-Commission VC Ultrasonics.

It is based on the *Handbook on the Ultrasonic Examination of Welds* (for carbon steel welds). Publications, practical experience, and available codes on ultrasonic examination of austenitic welds have been taken into account during preparation. The Handbook is intended to serve as a guideline for the preparation of procedures for specific applications but is not intended to provide a detailed inspection procedure for any particular weld.

Advice is given on how to devise procedures to take proper account of access available to the weld and of surface preparation. Methods are defined to ensure reproducible sensitivity setting for the ultrasonic examination and to provide a means of judging the test result. Specific problems such as the effects of grain structure and spurious indications, and the application of special probes are mentioned.

In spite of the limitations still existing, the Working Group believes that publication of the Handbook should not be delayed until all the outstanding problems have been solved.

This will help to spread present knowledge to the benefit of the many industries and institutions involved in constructions using austenitic welds.

The Handbook is intended to encourage a more uniform approach which should lead to better conditions for balanced evaluation and comparison of results.

The latter is of prime importance in guiding further work aimed at improving ultrasonic techniques as well as making progress in welding technology with regard to the metallurgical aspects involved.

1. GENERAL

Until recent years, austenitic steel welds were widely regarded as uninspectable by ultrasonics. Research and development have made it possible for a useful level of examination to be carried out in many situations. In general, though, the methods are more complicated and the capabilities more limited than for the examination of welds in ferritic steel. The main practical implications of this are

(1) Welding procedure and preparation geometry have a strong influence upon the capabilities of ultrasonic examination, so that careful consideration of these factors at the design stage can be very beneficial to the examination.

(2) Many technical aspects of the examinations are strongly influenced by the particular weld

structure so that only skilled, specially trained operators with a full appreciation of the physical basis of the examination should be employed.

(3) The capabilities for defect detection, positioning and size assessment are more limited than for ferritic weld examination. So, monitoring the occurrence of small defects can rarely be used for the quality control of welds, as is usual with ferritic welds. Rather, it may be necessary to use fracture mechanics to set less rigorous defect acceptance standards for the particular component. These acceptance standards should be compatible with the limitations of the ultrasonic techniques.

(4) The limited capabilities imply that it is prudent to supplement ultrasonic examination with radiography and surface examination techniques to a greater extent than is necessary with ferritic welds.

2. INTRODUCTION

2.1 Scope and Application

This Handbook gives recommendations for the ultrasonic examination of austenitic welds by manual scanning techniques which use the pulse-echo method and A-Scan presentation. The same recommendations can be extended to mechanical scanning techniques if special procedures are prepared for the data recording system.

The Handbook advises on how to devise procedures for the detection, location, and evaluation of ultrasonic indications of weld defects. Techniques involving the use of advanced instrumentation for signal processing might give better detection and identification of flaws but are not covered in this document.

The applications covered are limited to butt welds with weld metal of similar composition to the parent material. For dissimilar weld metals or for non butt weld geometries, procedures may be based on the general advice of this Handbook, provided attention is paid to the requirements of the specific geometry and material.

The recommendations given are primarily aimed at post fabrication rather than in-service inspection. Many sections of the Handbook will be relevant to both situations, but consideration of the specific problems of in-service inspection is outside the scope of this document.

This Handbook does not contain defect indication acceptance criteria.

2.2 Particular Problems Involved in the Examination of Austenitic Welds

The term *austenitic* covers a variety of materials and material combinations, including austenitic stainless steels and nickel chromium alloys such as "Inconel", "Incoloy", etc. The capabilities of ultrasonics for the examination of welds in austenitic materials are restricted compared to the ferritic case because of the presence of large elongated anisotropic grains (dendrites), often forming an ordered columnar structure, which are characteristic of the austenitic weld metal. This type of grain structure can lead to anisotropic ultrasonic behavior contrasting with the isotropic behavior of homogenous welds made in carbon or low alloy steels.

The size, the arrangement, and the elastic anisotropy of the different grains result in high scattering associated with mode conversion effects, beam distortion, and a variation of ultrasound velocity with direction and position in the weld. The scattering of energy is observed as a relatively high noise level (grass) and high attenuation.

The problems which occur in ultrasonic testing of austenitic welds differ according to the parent material production method (rolled, drawn, forged, or cast), the weld processes, and the heat treat-

ment as well as the composition of the parent and weld metals.

The guidelines given in this Handbook take account of the above factors to indicate how optimum test procedures can be prepared.

2.3 Principle of the Method

The ultrasonic methods applied to austenitic welds follow basically the same principles as those described in the *Handbook on the Ultrasonic Examination of Welds*. Some important differences do exist, however, which influence the ultrasonic method to be used and have implications for the capability of ultrasonics to detect, locate, characterize, and to estimate the size of weld defects. The most important of these differences are the following:

(1) Scattered energy from natural metallurgical discontinuities generates noise indications at higher amplitude than would be expected for the case of ferritic welds. The choice of wave mode (longitudinal, shear) and probe characteristics (sound field, frequency, bandwidth, etc.) should be optimized to allow a reliable separation of weld

defect indications from noise indications (see section 4.2).

(2) The ultrasonic beam has to cross different regions in the parent metal and in the weld itself. The velocity of sound may vary along this path (see section 4.2) and this may change the direction of the sound beam. Consequently, this may result in inaccuracy in determining reflector positions.

(3) Attenuation in the weld metal is generally more severe than for ferritic welds and can be more or less pronounced depending on the angle of the beam with respect to the preferred orientation direction of the grain structure. Therefore, the ultrasonic technique should seek to minimize beam path length in the weld metal and, where possible, aim to take advantage of any directions of reduced attenuation in the weld.

(4) Beam divergence can also be directionally dependent. The beam profile is usually different from that measured in parent plate (whether ferritic or austenitic) so that size estimation methods which depend on a knowledge of the beam profile, such as the so-called dB drop methods, are not always suitable on austenitic welds.

(5) Conventional instruments are used for examinations, but in most cases, special probes need to be applied (see section 5.3).

3. CONDITIONS TO BE ESTABLISHED PRIOR TO THE EXAMINATION

Since austenitic weldments present greater difficulties for ultrasonic testing than ferritic ones, the preparation of ultrasonic procedures requires more attention. In general, it is considered of great importance that operators should be informed about relevant details of weld fabrication, as given in section 3.3.2. Particular written procedures which specify the examination conditions and detailed ultrasonic techniques must be prepared in conjunction with metallurgists and NDT operators and need to take account of information that can be considered as fabrication know-how.

3.1 Personnel

The personnel applying this type of examination should be chosen from the best teams of

ultrasonic operators and be qualified at least to level two or equivalent. Their organization should submit them regularly to requalification tests particularly oriented to austenitic materials. As well as having good qualifications and sufficient experience in ultrasonic techniques, the personnel concerned should be trained on representative samples of austenitic welds to acquire specific experience in distinguishing defects from noise and spurious indications. For this they need the following:

- to be familiar with refraction/reflection rules and mode conversions
- to have experience in the use of specialized probes (e.g. angled longitudinal wave probes) and flaw detectors (e.g. selectable bandwidth)
- to have received appropriate instruction in the metallurgy of this type of material in order to be capable of determining the best approach for the examination, including how to relate defects and indications in the weld and in the parent metal
- to know the capacity of other NDT methods

which complement ultrasonics and the particular difficulties of these methods for austenitic materials ("wetting" behavior for dye penetrant examination — mottling and dark lines for radiography)

Supervisory personnel are strongly advised to keep themselves informed of new trends in methods of inspection, the evolution of equipment, and the development of new welding techniques.

3.2 Required Information About the Welds

As described in section 4, the effect of the material structure on ultrasound propagation is significant in this type of weld and, in addition, depends strongly on the geometry of the weld.

To obtain an effective ultrasonic technique with optimum flaw detection capabilities (e.g. choice of optimum probe parameters), it is necessary to collect maximum information on the weld characteristics.

(1) *Weld Geometry*. Selection of probe parameters depends on weld preparation and on the degree of penetration. On the drawing of the preparation, the operator will add the expected modifications of the fusion line introduced by the weld penetration. This depends on the nature of the filler material.

Particular attention should be paid to possible beam deviations resulting from the angle of the weld fusion faces. The extent of such difficulties can only be determined by experiment. Therefore, it is recommended that a weld sample be obtained wherever possible. Particular examples of problems associated with fusion face geometry are discussed in section 4.2. Furthermore, special problems can occur due to counterbore or weld root geometry in pipework. Details of root design should be obtained prior to ultrasonic examination.

(2) *Welding Process*. Knowledge of the weld process and procedure will contribute to an estimate of the likely grain structure (as discussed in section 4.1).

(3) *Heat Treatment*. Information on the heat treatment cycle is useful to provide an estimate of the parent material grain size. Using this information, the likely transparency can be assessed. Generally, fast quenching produces small grains, whereas maintaining high temperatures for a long time results in a large grain size.

The information required may be derived from representative weld samples as explained in section 7.3.

3.2.1 Welding Samples Available

The best way to obtain a sample is to take a section from the weld used as the welding procedure qualification block, or from a production weld. These samples should be as representative as possible of the weld to be examined in terms of weld preparation and process, procedure, geometry, heat treatment, heat input, etc. (See also section 7.3). The sample should be cut to produce macrographic sections perpendicular to the weld axis to show the structure and the weld fusion faces. Sections parallel to this axis may also be of value.

To obtain a good contrast, allowing the observation of columnar grains, fine polishing of the surface is necessary before etching.

3.2.2 Absence of Weld Samples

When it is not possible to obtain a sample of the weld to be examined, the above mentioned information should be obtained from the manufacturer or alternative sources.

3.3 Surface Preparation and Marking

Full volumetric inspection requires dressing of the weld crown. Only in this way can full access for scanning and adequate coupling be obtained.

Detailed requirements on surface preparation are specified in section 3.7.

When the weld is fully ground, the operator will not be able to visually identify the region to be examined (or a repaired zone) unless these areas are clearly marked.

It is considered good practice to mark the surface by punch marks. These marks may be made after completion of the weld to indicate the real fused zone of the weld. Alternatively, reference marks can be made at the stage of machining the weld preparation or counterbores, so that the position of the marks is known relative to a fixed datum such as the root face. If this is done, the center line of the reference marks should be clearly documented. When reference marks are absent, ultrasonic scattering methods or the use of a ferrite content meter can reveal the approximate weld position. Magnetic particle examination or careful chemical etching may be used to obtain more precise information on the weld limits.

The acceptability of any materials applied to the surface should be checked prior to use and residues subsequently removed.

3.4 Condition of the Parent Metal

To allow adequate penetration of ultrasonic waves into the weld, the parent metal should be

transparent to ultrasound and free from large flaws. Generally, rolled plate and forged pieces (medium thickness) are transparent, but this needs to be verified. Austenitic castings are generally hard to inspect because of the extremely coarse grain structure. As a guide, difficulties in penetrating parent material can become severe for grain sizes larger than ASTM 3 (average grain size 0.125 mm.)

To check the transparency of parent metal, an ultrasonic examination should be done using the same frequency and wave mode as for the examination of the weld. The velocity of ultrasound in the parent material should be measured with a normal beam probe to enable defects to be correctly positioned. The possibility of direction dependence of the acoustic properties of the parent material needs to be considered. After adequate transparency 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 base 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 based on a reflector size equal to that used for the weld examination. This should have been taken into consideration prior to cutting the base metal.

If localized variable attenuation is observed along the examined zone, the value must be taken into account to correct the sensitivity of the weld examination.

3.5 Agreements before the Start of the Examination

To avoid misunderstanding and arguments about the examination to be carried out, a number of conditions or directives need to be established prior to the examination.

3.5.1 Extent of the Examination

Generally, the extent of the examination will be determined in the first place by the degree of certainty to be achieved with regard to the absence of unacceptable defects.

The procedure to be established and the equipment to be used should take account of the criteria which the customer and inspecting authority require. For difficult examinations, this is likely to involve detailed discussion on flaw acceptance criteria and ultrasonic acceptance criteria.

The extent of the examination also refers to the total length to be examined, the degree of volumetric examination, the necessity to examine par-

ticular zones more carefully, etc., and also to special requirements such as checks by other operators, or alternative techniques or different equipment. Much depends on the type of weld, the situation in which it has to be examined, its ultimate service, and the possibilities of statistical control.

Ultrasonic examination of austenitic welds can cost more than that of similar ferritic welds because of the necessary preparatory work described later on. The greater the extent of the examination, the required sensitivity, or the details to be reported, the longer will be the examination time.

To avoid unnecessary expense, the aim should be to restrict these requirements to an acceptable minimum. It is, therefore, advisable to adopt different classes of examination in such situations, whereby structures may be examined according to the importance of individual welds in the component (see also section 4).

3.5.2 Sensitivity Required

The sensitivity is mainly determined by the smallest allowable defect and its position in the weld. However, not only are thickness, size, and length of defects important, but also their nature and orientation.

The sensitivity setting does not alone determine the ability to detect certain defects. Also involved are material characteristics and the whole technique applied, i.e., the frequency and wave mode used, the probe angle, the scanning technique (with one or two probes), etc. The ideal way to determine the required or practicable sensitivity is to use reference welds (see section 7.3), of the same configuration and material, welded by the same procedure and containing real defects of the maximum acceptable size.

However, this is often impracticable, and therefore levels of sensitivity which can be established with good reproducibility are mostly accepted as the appropriate solution. These levels are based on the reflections obtained from reference targets such as side drilled holes or flat-bottom holes of specified size. The levels to be set should bear a realistic relationship to the importance of the weld to be examined and should be agreed upon prior to the examination. Systems in use for sensitivity setting are described in section 7.6.

3.5.3 Special Conditions

Before commencing the examination, agreement should also be reached on the following points:

- Surface dressing (3.7)
- Coupling media to be used (3.8)
- System of marking welds (3.3)
- System of indicating defects found
- Examination of welds or parts of welds to which access is difficult or which are, for other reasons, difficult to examine
- Use of other NDT methods

3.5.4 Regular Check of Equipment

Regular checking of the performance of ultrasonic defect detection equipment is very important and should be agreed before the start of the examination. Various national and international standards or recommendations exist which might be used as a basis.

The recommendations in section 6 may be used to supplement these in order to meet the specialized requirements of austenitic weld inspection.

3.5.5 Reporting

The extent of the details to be recorded during the examination greatly influences the time required for a manual examination. After agreeing on the sensitivity for a particular class of work, only those defects producing echoes exceeding an agreed registration level should be reported in detail. It is therefore not advisable to call for reports containing detailed information on all possible indications with the aim of subsequently analyzing them and identifying acceptable defects.

Recommendations on the contents of a typical report are given in section 9. The object of this paragraph is to make it clear that this matter should be agreed upon prior to the examination.

3.6 Visual Inspection

The visual appearance of the welded joint should be recorded with particular reference to visible defects and the shape of the weld, e.g. surface curvature, degree of root penetration, backing ring, different parent metal thicknesses, extent

of the reinforcement, presence of undercut, weld finish, and alignment of parts.

3.7 Surface Preparation

The material surfaces to be used for the scanning procedures chosen must allow free movement of the probe(s) and provide satisfactory conditions for the transmission of the ultrasonic waves. Therefore, the surface roughness should generally not exceed $20\text{ }\mu\text{m}$ and the waviness should not exceed $\pm 0.5\text{ mm}$ over any area of $50\text{ mm} \times 50\text{ mm}$. This is necessary to avoid disturbance of the ultrasonic beam which could reduce the sensitivity and result in errors in defect location. Where there is access to only one surface of the weld, any weld reinforcement must be ground off if the whole weld volume is to be examined and if shear waves cannot be applied. This is because mode conversion losses on reflection reduce the effectiveness of examination in the second traverse with angled compression waves.

Furthermore, on each side of the weld for a minimum of 5/4 skip distances, 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.

3.8 Couplants

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 couplants include water, oil, grease, and glycerine. The couplant used should form a film between the probe and 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. Couplants containing halogens are to be avoided.

4. ULTRASONIC PROPAGATION BEHAVIOR

4.1 The Structure of Austenitic Welds

Austenitic weld metal is generally a coarse-grained material which often displays ordered

columnar grains when examined metallographically. Sometimes, extended grain growth occurs whereby columnar grains traverse several weld beads.

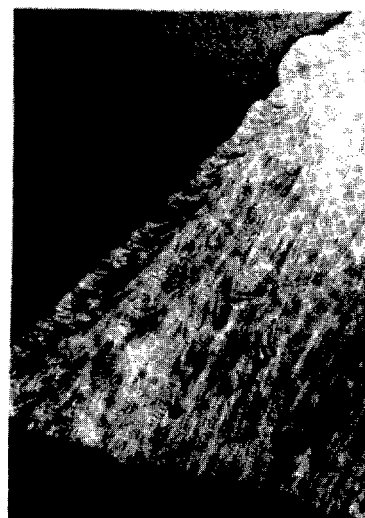
In principle, the coarse grain structures may be broken up by mechanical deformation or modified by heat treatment to above 1050°C , but such processes are not usually practicable. The grain



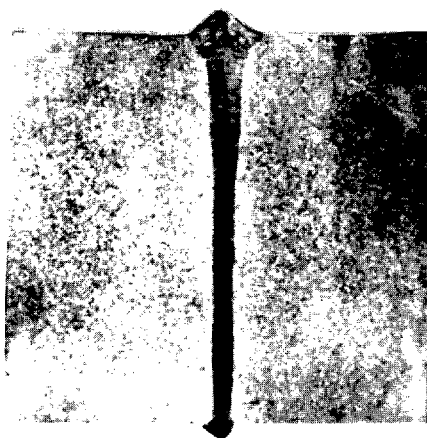
SUBMERGED ARC BUTT WELD



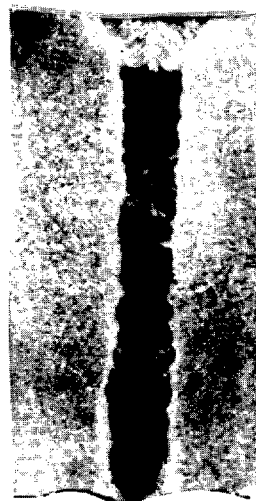
DOWNHAND SMA WELD



HORIZONTAL-VERTICAL
SMA WELD



ELECTRON BEAM WELD



GTA WELD

NARROW
GAP
WELDS

**Figure 4.1 — Macrographs of a selection of austenitic welds,
showing a variety of shapes for the fusion line**

structure orientation is not random and different types of welding procedures produce their own characteristic patterns. Generally, columnar grains will start to grow perpendicular to the surface of the weld preparation. However, they may gradually alter their direction in a manner depending on the welding process and the related heat flow during solidification.

(a) **SHIELDED METAL ARC WELDING (SMAW)** generally forms small weld beads compared to the other mentioned welding processes, with columnar grains extending from one bead to the next to give a highly aligned structure.

(b) **AUTOMATIC SUBMERGED ARC WELDING (SAW)** generally results in larger weld beads with the grains within each bead forming a fan shaped structure. Grain extension across the layers of the weld beads is less pronounced than for shielded metal arc welds. Depending on the weld current, some submerged arc welds can have a grain structure closely resembling that of the SMA type.

(c) **GAS SHIELDED ARC WELDING (GSAW)** weld runs, especially in the root region, can give a locally fine grain structure. Where the bulk of the weld metal is deposited by the TIG process, the likely structure will be that of a fan shaped arrangement of the grains within each weld bead with little grain extension between adjacent weld beads.

(d) **ELECTROSLAG WELDING (ESW)** results in a very different grain structure from the above process since there is a tendency for the grains to grow parallel to the weld preparation surfaces.

Figure 4.1 shows a selection of weld macrographs. Note that a major change of structure exists at the fusion face. This will influence the ultrasonic behavior as described in section 4.2.1.4.

Experiments have shown many similarities between ultrasound propagation in large single crystals and in a well ordered weld structure of elongated grains. It is difficult to produce two welds which are identical with regard to their structure.

For instance, Figure 4.2A represents diagrammatically the differences in grain structure produced by small changes in a manual welding procedure. This difference in grain orientations brought about by differences in the welding sequence as illustrated in Figure 4.2B, has an influence on sound propagation as indicated by the dotted lines in Figure 4.2A.

The so-called "skewing" of the beam is a result of multiple refraction at successful grain boundaries. The greatest care must therefore be taken when producing and using reference blocks to

simulate austenitic weld fabrications. See section 8.4.

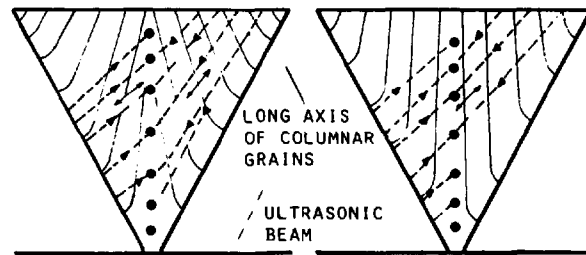


Figure 4.2A — Diagram of two downhand SMA welds showing differences in grain orientation and resulting sound path



Figure 4.2B — Example of differences in the sequence of bead placement bringing similar differences as illustrated in Figure 4.2A

4.2 Effects of Austenitic Structures on Ultrasound Propagation

The effect of austenitic structures on the behavior of ultrasound depends largely on grain size. Small grains, as found in rolled plate, have no adverse effect on sound propagation. On the other hand, coarse grain cast structures and those in the welds which have been described in the previous section have marked effects, leading to increased scatter and attenuation, variations in sound velocity, and often to beam-distortion.

The effects are primarily due to the anisotropic nature of the austenitic grains, as will be explained in the following sections.

4.2.1 Ultrasound Propagation in an Anisotropic Structure

In marked contrast to ferritic materials where a constant sound velocity is normally assumed,

many of the ultrasonic characteristics of austenitic welds derive ultimately from the anisotropic elastic properties of the columnar grains which form the weld. These grains have minimum dimensions which are usually comparable to the wavelength of the ultrasound, or somewhat smaller, while the width of the ultrasound beam usually covers several grains. The resulting mode conversion and scattering effects at grain boundaries are important sources of noise and of spurious indications.

Even for simple models of austenitic welds produced by the downhand SMAW process, the exact mathematical representation of their elastic properties and resultant ultrasonic behavior is very complex. The effect of the austenitic welds structure is that ultrasound propagation is sensitive to the angle of the wavefront with respect to the grain axes. The dependence on this angle changes dramatically as the wave mode under consideration is changed from the common vertically polarized shear waves (SV), to longitudinal waves (L) and to horizontally polarized shear waves (SH). An important factor is that when traveling through the coarse grained anisotropic material the wavefronts are not generally at right angles to the beam axes. This means that the effective direction of the beam (maximum energy flux) in anisotropic weld metal can differ from the nominal beam direction (see Figure 4.3).

Although these phenomena are evident from simple pulse echo observations, their nature is complex and can usually only be readily demonstrated using special test pieces. Figure 4.4 illustrates components for a demonstration which has been found useful for this purpose. The specimens are machined from weld metal laid down to produce a block with highly oriented grains.

A cube with several edges and corners machined off at 45° to the various faces can also be used to illustrate the directional dependence of velocity and the attenuation of both compression and shear waves.

4.2.1.1 Variation of velocity

Elastic anisotropy leads to variations in the propagation velocity of ultrasound waves. In general, the propagation velocity depends on the angle between the wave front and the major axes of the columnar grains.

The machined cube specimen referred to above may be used to measure the velocity in a number of directions. It gives results at 45° intervals for the principal axes of the specimen. By rotating cylindrical specimens with the probes fixed, the apparatus shown in Figure 4.4 may be used to study the large variation of compression wave velocity in the planes normal to the specimen axes.

Figure 4.5 illustrates the angular variations calculated in more detailed studies of highly oriented material.

4.2.1.2 Beam direction

If a specimen made from rolled austenitic or ferritic plate is rotated in the apparatus shown in Figure 4.4 (using a conventional couplant), no systematic variations will be observed on the screen of a flaw detector connected in transmission mode to the two probes. Also, the maximum signal amplitude will be received with the receiving transducer on the axis of the apparatus.

Very different results are obtained for two of the three specimens shown in Figure 4.4(A). In addition to the effect of the varying velocity referred to

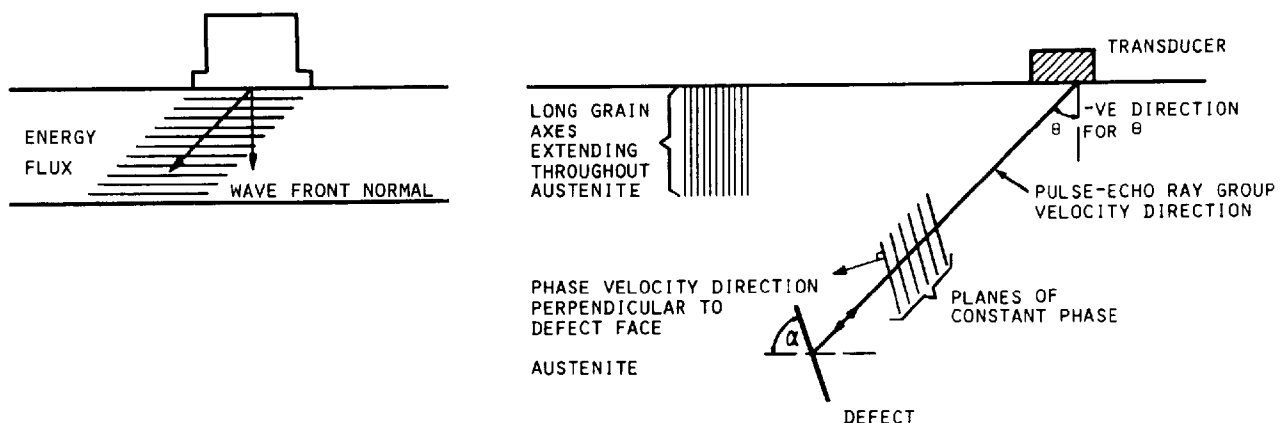


Figure 4.3 — Visualization of the wave front normal and the direction of energy flux, i.e. "propagation direction" (left: normal beam, right: angle beam)