

# Phased Array Ultrasonic Testing of Austenitic Stainless Steel Welds of the 11 T HL-LHC Dipole Magnets

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# **Phased Array Ultrasonic Testing of Austenitic Stainless Steel Welds of the 11 T HL-LHC Dipole Magnets**

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June 2018

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Phased Array Ultrasonic Testing of Austenitic Stainless Steel Welds of the 11 T HL-LHC Dipole Magnets

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**Sammanfattning**  
Abstract

A routine non-destructive test method based on Phased Array Ultrasonic Testing (PAUT) has been developed and applied for the inspection of the first 11 T dipole prototype magnet half shell welds, and the test results are compared with the radiography and visual inspection results of the same welds.

A manual scanner and alignment system have been developed and built to facilitate the inspection of the 5.5 m long welds, and to assure reproducibility of the PAUT results.

Through the comparison of distance readings and signal amplitude for different focus lengths, a focal law with focus at 25 mm sound path has been selected for the routine inspection of the 15 mm thick austenitic stainless steel 11 T dipole welds. The defocusing properties (beam spread) due to the cylindrical geometry of the half shells and the sound path distance to the area of interest were taken into account.

Dedicated sensitivity calibration weld samples with artificial defects (side-drilled-holes) have been designed and produced from 11 T dipole prototype austenitic stainless steel half shell welds. These provide representative calibration for the strongly attenuating and scattering austenitic stainless steel weld material.

One scan with two phased array probes aligned parallel to the weld in 2 mm distance from the weld cap edge, and one scan with the probes aligned parallel to the weld in 12 mm distance from the weld cap edge are sufficient to show if the inspected welds fulfil the requirements of weld quality level B according to ISO 5817.

The standard test duration for the two scans of the two 5.5 m long horizontal welds of the 11 T dipole magnets is about one day, provided that no defects are found that need to be characterized in more detail.

**Nyckelord**  
Keyword

Phased Array Ultrasonic Testing (PAUT), non-destructive testing, austenitic stainless steel welds, CERN, HL-LHC, 11 T Dipole



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## ABSTRACT

A routine non-destructive test method based on Phased Array Ultrasonic Testing (PAUT) has been developed and applied for the inspection of the first 11 T dipole prototype magnet half shell welds, and the test results are compared with the radiography and visual inspection results of the same welds.

A manual scanner and alignment system have been developed and built to facilitate the inspection of the 5.5 m long welds, and to assure reproducibility of the PAUT results.

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Finally I want to thank my family and friends for always believing in me.



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## NOTATION

### CERN

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|        |                                                                                                                                                                               |
|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| CERN   | <b>European Organization for Nuclear Research</b> , or Organisation européenne pour la recherche nucléaire. Derived from: <i>Conceil Européen pour la Recherche Nucléaire</i> |
| TE     | <b>Technology Department</b>                                                                                                                                                  |
| MSC    | <b>Magnets, Superconductors and Cryostats</b>                                                                                                                                 |
| LMF    | <b>Large Magnet Facility</b>                                                                                                                                                  |
| LHC    | <b>Large Hadron Collider</b>                                                                                                                                                  |
| HL-LHC | <b>High-Luminosity Large Hadron Collider</b>                                                                                                                                  |

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### Ultrasonics

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|      |                                                                                                                                                    |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------|
| NDT  | <b>Non-Destructive Testing</b>                                                                                                                     |
| PA   | <b>Phased Array</b>                                                                                                                                |
| UT   | <b>Ultrasonic Testing</b>                                                                                                                          |
| PAUT | <b>Phased Array Ultrasonic Testing</b>                                                                                                             |
| DMA  | <b>Dual Matrix Array</b>                                                                                                                           |
| CFU  | <b>Couplant Feed Unit</b>                                                                                                                          |
| HAZ  | <b>Heat-Affected-Zone</b>                                                                                                                          |
| FSH  | <b>Full-Screen-Height</b>                                                                                                                          |
| SDH  | <b>Side-Drilled-Hole:</b> an artificially produced defect simulating volume defects such as pores, inclusions, shrinkage cavity etc.               |
| FBH  | <b>Flat-Bottomed-Hole:</b> an artificially produced defect simulating flat defects such as cracks and Lack-of-Fusion in the weld bevel.            |
| LOF  | <b>Lack-Of-Fusion:</b> an area of the weld which has not fused to the parent material. Occurs typically at the weld bevel and between weld passes. |

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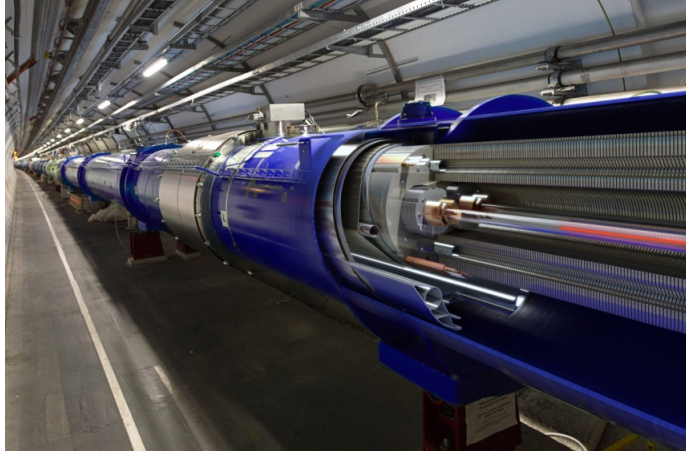
# 1

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## INTRODUCTION

CERN, the European Organization for Nuclear Research<sup>1</sup>, is the worlds largest particle physics laboratory situated just outside Geneva, Switzerland. With over 10,000 visiting scientists, users, fellows and students representing over 600 universities from all over the world, the frontiers of fundamental physics is being explored.

The Large Hadron Collider (LHC) shown in figure 1.1, accelerates two beams of protons clockwise and counter clockwise to an energy of 7 TeV each in the 27 km circumference accelerator and is made to collide in four experiments: ATLAS, CMS, ALICE and LHCb.



**Figure 1.1:** Picture from the LHC tunnel showing a computer rendered cross section of the inside of LHC. A hint of the curvature of the accelerator can be seen. [1]

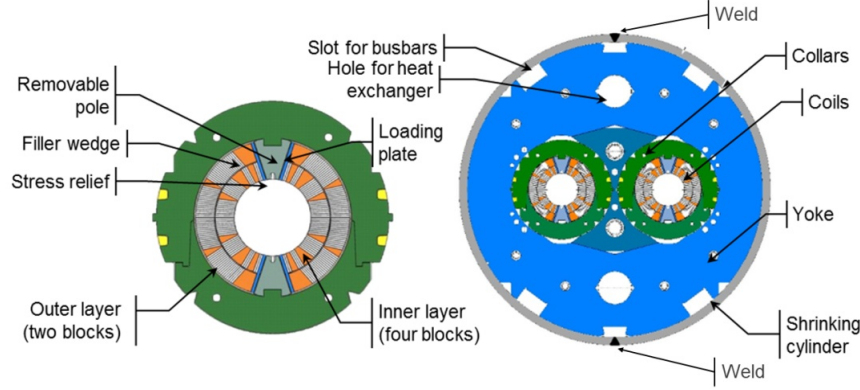
The LHC is undergoing a luminosity upgrade in the High Luminosity project (HL-LHC) [2] and one part is installing a new collimation system. To make room in the accelerator, 5-10 main bending magnets will be replaced by new stronger 11 Tesla (T) dipole bending magnets. [3, 4] The luminosity of an accelerator is proportional to the number of collisions per unit time and with the HL-LHC it is increased with a factor of 6-8 compared to the current LHC. [5] The increased amount of data collected by the experiments due to the higher luminosity, increase observations of rare events such as production of the Higgs boson.

A cross-section of the 11 T dipole magnets is shown in figure 1.2 where the two superconducting magnet coils are collared and placed in a ferromagnetic yoke. The full assembly are closed by two hot rolled and folded austenitic stainless steel AISI 316LN (X2CrNiMoN17-13-3) half shell cylinders [6],

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<sup>1</sup>Conseil Européen pour la Recherche Nucléaire

TIG-welded (Tungsten Inert Gas) together under large pressure. The welded half shells are noted with *Shrinking cylinder* in figure 1.2. The magnet components and its enclosure has to withstand cooling from room temperature down to 1.9 K using super-fluid helium and large forces from the magnetic fields when the magnet is operated. The enclosure must hold high quality homogeneously throughout the steel cylinder.



**Figure 1.2:** A schematic image of the cross-section of the 11T dipole. The austenitic stainless steel half shells are noted with *Shrinking cylinder*. [7]

A non-destructive quality control according to the pressure vessel codes [8] of these horizontal welds is necessary to ensure the required weld quality. Lack-of-fusions, pores and cracks are examples of defects that may appear in the weld volume.

The work presented in this thesis has been carried out in order to develop a test procedure for non-destructive testing (NDT) of these welds by Phased Array Ultrasonic Testing (PAUT) [9, 10]. The NDT must fulfil the following weld quality and testing requirements.

The standard *ISO 5817: Welding - Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) - Quality levels for imperfections*, [11] describes different types of imperfections that are common in welds and their dimensions of acceptance. Three quality levels, D, C and B denotes the requirements where level D has the lowest and level B has the toughest quality requirements. For the austenitic stainless steel welds of the 11 T dipole half shells the highest quality level (**B**) is chosen to conform to the pressure vessel standards [8].

*ISO 11666 - Non-destructive testing of welds - ultrasonic testing - Acceptance levels* [12] is a standard which is customized to the advantages and limitations of ultrasonic testing and serves as a link between the quality level in ISO 5817 and the practical ultrasonic tests. The signal amplitude of the echo from a defect is compared to a reference level that is set during sensitivity calibration. In addition, reference blocks are used to compare the signals from natural defects to artificial defects of known size.

*ISO 17640 - Non-destructive testing of welds - Ultrasonic testing - Techniques, testing level, and assessment* [13] describes how the probe should be placed in relation to the weld, at what angles and distances for the inspections. Calibration is briefly explained in this standard but for details of sensitivity calibration the standard *ISO 22825 Non-destructive testing of welds - Ultrasonic testing - Testing of welds in austenitic steels and nickel-based alloys* [14] is used.

More information on quality and testing requirements is found in appendix A - Weld Quality and Testing Requirements.

The beam formation and propagation of ultrasound in the austenitic stainless steel weld cause a large noise level but can be suppressed to acceptable levels using correct equipment and equipment settings. Water is used as coupling medium for the ultrasonic beam. To ensure a good coupling, the surface of the weld area is prepared before testing.

Longitudinal compression waves are used for the austenitic stainless steel. However only the first leg of the ultrasonic beam can be used with good certainty i.e. no skipping on the back wall. Because of the strong attenuation in the weld material and because of mode conversion from longitudinal waves to shear waves when the beam is skipped on the back wall, these signals can only be used as an indicator of the presence of defects and is cause for further testing of the area.

The PAUT results are compared with radiography results of the same welds including detectability of different defects and a small discussion of the two methods advantages and disadvantages are given.



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# 2

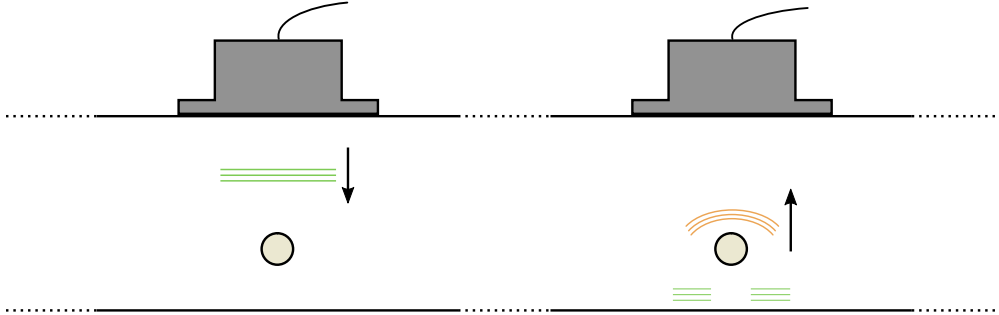
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## THEORY

### 2.1 Basics of Ultrasonic Testing

Ultrasonic testing often use a pulse-echo technique for defect detection in materials such as metals and plastics. A pulse of sound produced by a probe is coupled into the material and propagates throughout the volume. If a reflector, e.g. a defect or the back wall, is present in the sound path, a sound-echo can return to the probe which generate a measurable electrical signal. The location of the reflector can be calculated by the time difference between sending the pulse and receiving the echo while knowing the angle of the beam and the velocity of sound in the material as shown in figure 2.1.

Only the interface of the defect with surface area perpendicular to the sound beam in figure 2.1 will produce an echo that travels back to the probe. Therefore multiple positions and/or angles can be used to create a map of the defect and determine the size.



**Figure 2.1:** Pulse-echo technique. The probe emits a sound pulse into the test material. When the sound beam strikes a defect in the test piece an echo is produced which then return to the probe.

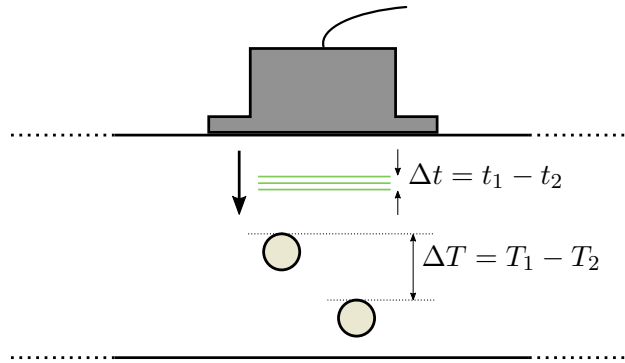
#### 2.1.1 Sound Creation and Resolution

The active part of an ultrasonic probe, the transducer, most commonly consists of a single piezo-electric crystal. An applied electric field across the crystal changes its shape which can be used to create sound. Other types of probes exists such as electromagnetic acoustic transducers and laser transducers [15]. A good example of a piezo-electric crystal is quartz which was used in ultrasonic probes from late 1920 to the end of the 1950s. Thereafter more sophisticated polycrystalline transducers has been developed which has a lower resistance to higher frequencies, increasing the performance of up to 70%. Usually the crystal is cut in such a way that the expansion and contraction is directed towards the test material. When operated it will produce longitudinal compression waves. [15]

The pulse of sound is generated by applying a sharp electrical pulse to the piezo-electric crystal which then starts to oscillate at its own resonance frequency,  $f_{res}$ , determined by the crystal thickness,  $t_{piezo}$ , and the compression wave velocity,  $V_{piezo}$ , inside the piezo-crystal. By reducing thickness, the resonant frequency increase as described by equation 2.1, [15]. Typical useful frequencies for ultrasonic inspection range from 500 kHz to 20 MHz [16], and the diameter of the transducer range from 6 mm to 13 mm, and even larger up to 25 mm in diameter for certain applications. It should be noted that the crystal does not produce sound waves of only the exact resonant frequency. Rather it is a range of frequencies centred to the resonant frequency, called the bandwidth of the transducer.

$$f_{res} = \frac{V_{piezo}}{2t_{piezo}} \quad (2.1)$$

The sound waves are coupled from the transducer into the test material using a liquid. The atoms in the liquid start to oscillate at the same frequency as the crystal and eventually as the vibrations propagate they are coupled into the test material. It is important to have a low pulse length of the sound wave, i.e. to keep the number of resonant vibration periods low, typically 1 to 5, because the pulse length determine the resolution of the inspection. For example two defects close to each other as shown in figure 2.2. The time difference between the front and back of the pulses  $\Delta t = t_1 - t_2$ , must be smaller than the time difference between reaching the two different defects  $\Delta T = T_1 - T_2$ . The pulse length,  $\Delta t$ , can be calculated as the product between number of periods,  $N$ , and wavelength,  $\lambda$ , in the material being inspected ( $\Delta t = N * \lambda$ ). The piezo-crystal of a conventional probe will normally have 12 or more periods depending on crystal diameter and excitation method among others, which in most cases are too many. Therefore, by applying a backing material on the backside of the crystal the number of periods is reduced through damping. [15, 9]



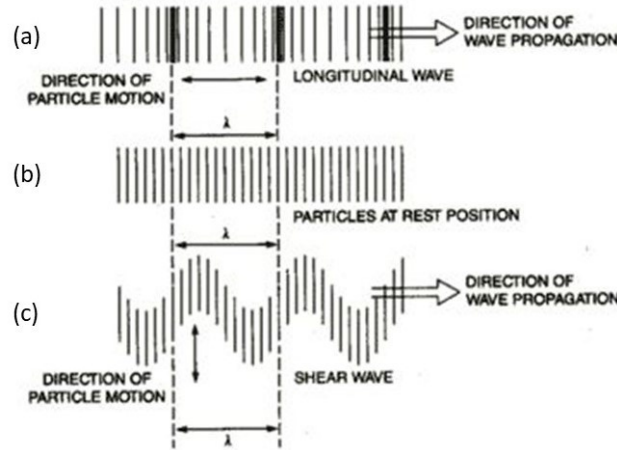
**Figure 2.2:** To distinguish between the two defects the relation:  $\Delta t < \Delta T$  must be fulfilled.

### 2.1.2 Huygen's Principle

According to Huygen's principle, each point of an advancing wave-front acts as a point source of sound, emitting a new spherical wave. The resulting wave is the superposition of each of the secondary waves. [9, 17] If the transducer is big compared to the wavelength, the result will be an almost straight beam. Nearly all of these "point sources", except the ones at the edges of the crystal, will experience constructive interference only parallel to the path of propagation and form a uniform wave-front. However, if the transducer is small compared to the wavelength the result will become more of a spherical wave. A special case arise when using a rectangular transducer which can be considered big in one direction and small in the other and will therefore act as a line source, creating cylindrical waves. This will become important in section 2.2.

### 2.1.3 Modes of Propagation and Velocity

Two types of sound waves are mainly used in ultrasonic inspection, longitudinal compression waves shown in figure 2.3(a) and shear waves shown in figure 2.3(c). Figure 2.3(b) show the particles in their rest positions.



**Figure 2.3:** Illustration of (a) longitudinal compression waves, (b) particles at rest and (c) shear waves. [18]

Longitudinal compression waves propagate through the material by compressing and de-compressing atoms in the same direction as the propagation of the wave. The force exerted by the distorted atoms on its neighbours is due to the atomic bonds. Depending on the strength of the bond, materials will have different resistance to compression and stretching called the Young's modulus of Elasticity. [16] Compression waves propagate faster with increasing modulus of elasticity. Consider a linear chain of atoms connected by identical springs. Increasing the spring constant makes the chain more rigid and a distortion can propagate faster.

Shear waves on the other hand propagate through a solid material by displacing, shearing, the atoms perpendicular to the propagation of the wave. The solids resistance to shearing is described by the Modulus of Rigidity. Compared with compression waves, shear waves propagate much slower, as a rule of thumb, half the velocity. The sound velocity of the two modes does not only depend on "spring constant" but also on density of the material, and mass of the atoms, [16].

Creeping waves is a special type of compression wave which "creeps" along the surface of the inspection material and can be quite useful for detection of surface and near surface defects. They are treated in section 2.2.4. Other modes of propagation exists, e.g. surface wave mode and lamb wave mode, but are much less utilized in ultrasonic inspection and is not covered in this thesis.

As compression waves are associated with approximately twice as large velocity compared to shear waves and calculating the wavelength using equation 2.2, compression waves also have a longer wavelength for the same frequency probe.

$$\lambda = \frac{v}{f} \quad (2.2)$$

Long wavelength ultrasound is less affected by features in the material like grain boundaries, micro cracks and larger defects, and therefore have a deep penetration but also have a problem detecting very small defects. Generally, a defect is considered detectable if its reflecting surface is bigger than half a wavelength. [10]. Hence, when choosing wavelength and type of wave mode, a trade-off between detectability and length of propagation has to be made. This also depends on the

material to be inspected, some materials have large grains and many small features which result in a higher attenuation than others with small grains and few features.

### 2.1.4 Acoustical Coupling

Liquids and gases have no modulus of rigidity, therefore shear waves cannot propagate through them. They do however have a resistance to compression and stretching, i.e. elasticity, and therefore also support compression waves! As mentioned earlier, ultrasound is coupled from the probe to the inspected material using a liquid. The reason for this is to match the acoustical impedance,  $Z_i$ , between probe and test piece. Equation 2.3 is used to calculate the percentage of reflected sound energy,  $E_R$ , when a wave encounters an interface between two materials, and is completely determined by the matching of the acoustical impedance. The percentage of transmitted sound,  $E_T$ , is given by equation 2.4.

$$E_R = \left( \frac{Z_1 - Z_2}{Z_1 + Z_2} \right)^2 * 100\% \quad (2.3)$$

$$E_T = 100\% - E_R \quad (2.4)$$

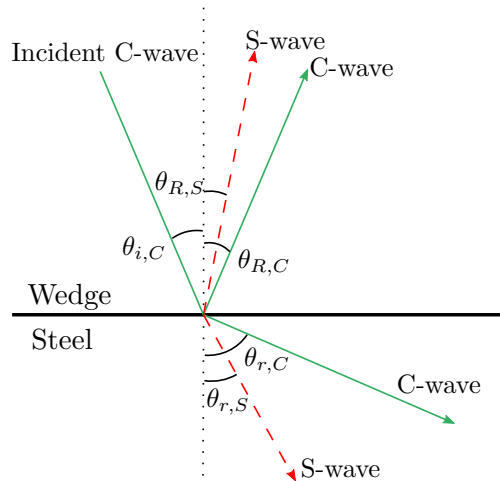
where  $Z_1$  and  $Z_2$  are the impedances of material 1 and 2 respectively. The impedance mismatch between air ( $Z = 0.0004$ ) and metal ( $Z = 44.8$  for stainless steel) is very high meaning that almost all energy is reflected. The mismatch between water ( $Z = 1.48$ ) and stainless steel is much less but will still have an energy reflection of about 88%, meaning that only 12% of the energy is usefully transmitted. Echoes returning from a defect experience the same reflection and transmission, so only 12% of this is usefully transmitted back to the probe. In total, using the best couplant (e.g. glycerin) at optimal conditions, just above 2% of the energy will come back to the probe. [19] If water is used as a couplant, the number is closer to 1.5%.

### 2.1.5 Snell's Law and Mode Conversion

A sound beam incident on an interface of two materials with different sound velocities will be reflected and refracted according to Snells law, see equation 2.5.

$$\frac{\sin(\theta_i)}{v_i} = \frac{\sin(\theta_r)}{v_r} = \frac{\sin(\theta_R)}{v_R} \quad (2.5)$$

where  $\theta_i$ ,  $\theta_r$  and  $\theta_R$  are the incident, refracted and reflected beam angle respectively and  $v_i$ ,  $v_r$  and  $v_R$  the respective speed of sound in the material of propagation. A beam exiting a low velocity and entering a high velocity material, like wedge (plastic rexolite) to steel, will be refracted to a greater angle as shown in figure 2.4, and vice versa. Also, mode conversion takes place meaning that an incident compression (C-wave) or shear wave (S-wave) will, at the interface, partly convert into the opposite mode, both for the reflected and refracted beams. [20] Since compression and shear waves have different velocities they will be refracted and/or reflected at different angles. For example the shear wave is reflected at a smaller angle because it travels with about half the speed of sound compared to the compression wave. From here on it will be assumed that the incident beam is compression mode.



**Figure 2.4:** Snell's law for a wedge (see section 2.2.3) to steel interface and incident C-wave. The reflected C-wave has the same angle as the incident beam, but the mode converted S-wave reflection is at a smaller angle due to the lower velocity. The high velocity associated with C-waves in the steel cause a large refraction angle, but small for the slower S-wave.

### Mode Conversion for Refraction

Parts of an incoming beam at a water-to-steel interface will, depending on the incident angle, be refracted and mode converted into shear waves. For low incidence angles in the water, the range of  $0^\circ$ - $9^\circ$ , the percentage of mode conversion is small, i.e. an incoming compression wave will mostly refract in compression mode. But as the incidence angle is increased, a larger percentage of mode conversion takes place. At around  $10^\circ$  in the water, mode conversion is strong enough to convert shear waves with sufficient amplitude to give "false" readings if a defect is present.

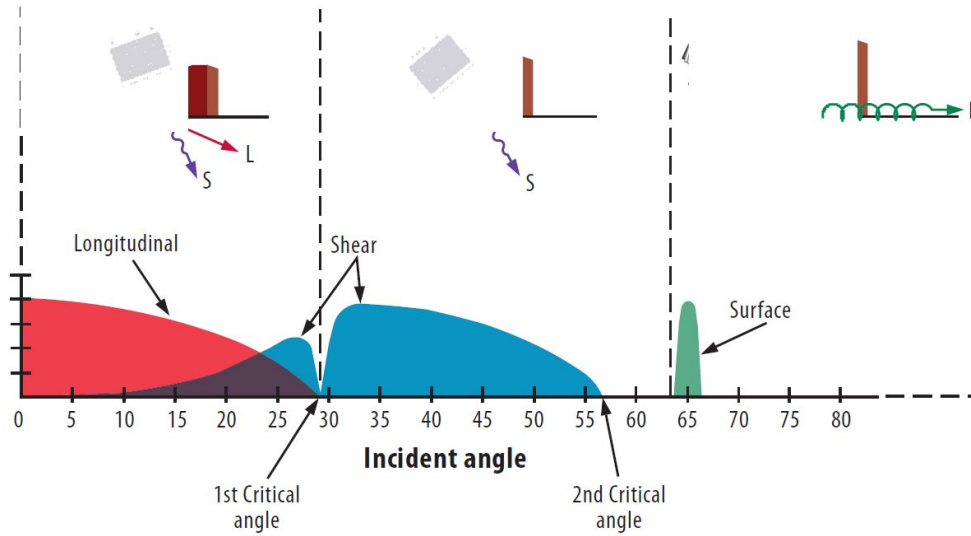
For an inspection with angled beams, a plastic wedge is commonly used, see section 2.2.3. Since the resulting beam angle in the sample, e.g. steel, is the same independent on choice of couplant, and only depends on the wedge angle, one can use the wedge angle as a reference. By using Snell's law to obtain the refraction angles for the interface between the wedge and couplant, e.g. water, (Eq. 2.6) and then for the interface between the couplant and the sample, e.g. steel, (Eq. 2.7) one can eliminate the term for the couplant (Eq. 2.8).

$$\frac{\sin(\theta_{wedge})}{v_{wedge}} = \frac{\sin(\theta_{water})}{v_{water}} \quad (2.6)$$

$$\frac{\sin(\theta_{water})}{v_{water}} = \frac{\sin(\theta_{steel})}{v_{steel}} \quad (2.7)$$

$$\implies \frac{\sin(\theta_{wedge})}{v_{wedge}} = \frac{\sin(\theta_{steel})}{v_{steel}} \quad (2.8)$$

Figure 2.5 illustrates mode conversion for different wedge angles. The first critical angle in a plastic rexolite wedge to steel interface is about  $28^\circ$  ( $15^\circ$  for water) where the compression mode waves suffer total internal reflection. At larger angles only shear waves are transmitted. There is also a second critical angle at  $57^\circ$  ( $28^\circ$  for water) where not even shear waves can exist and is eventually mode converted into surface (Rayleigh) wave. [20]

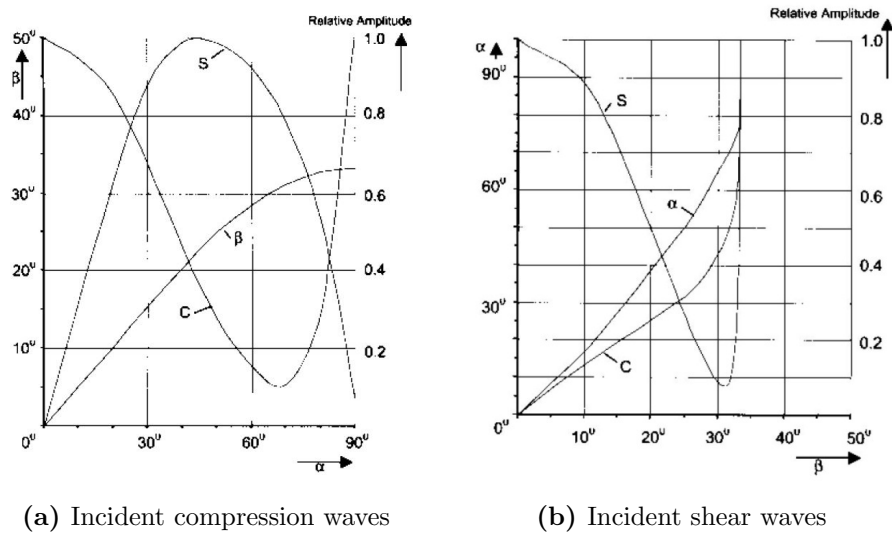


**Figure 2.5:** Mode conversion of refraction for a compression wave probe for different incidence angles. The x-axis is given in wedge angle, see 2.2.3. [9]

### Mode Conversion for Reflection

The mode conversion for reflection is a bit different from refraction. If the incident beam travel in a liquid, typically a couplant between probe and test object, there can be no mode conversion into shear waves since the liquid does not support shear waves. However, if there is an interface, e.g. steel to air in the form of a crack or a pore in a solid object, mode conversion for reflection can occur. Low incidence angle compression waves produce reflections in mostly compression mode, but as the angle increases so does the mode converted shear wave until a maximum shear mode is reached as shown in figure 2.6(a).

Shear waves at low incidence angles will analogously reflect in shear mode. Increasing the incidence angle means increasing amount of compression mode waves as shown in figure 2.6(b). [20]



**Figure 2.6:** (a) Mode conversion for reflection of an incident compression wave beam versus incidence angle. (b) Mode conversion for reflection of an incident shear wave beam versus incidence angle. [20]

### 2.1.6 Attenuation and Beam characteristics

The energy loss when the sound beam is propagating through a material, i.e. attenuation, is caused by absorption, scattering, interference effects and beam spread [21].

#### Scattering and Absorption

Scattering depends on the size of the grains in the material where larger grains result in a larger scattering effect. This is because the grain boundaries of very large grains are wide and therefore result in a more prominent interface where reflection and refraction can occur. Absorption depends on the elastic properties of the material and is due to the movement of the atoms which continuously require energy. Longer wavelengths are less affected by the grain boundaries, and have lower absorption, so for a highly attenuating material one has to choose a probe with long wavelength, i.e. a low frequency. [21]

#### Beam Spread

Another "attenuating" factor is the beam spread. As the beam propagates it spreads out in a conical shape and sound energy in any point in the path gets weaker. The inverse square law of intensity versus distance, known from e.g. a beam of light, applies to the ultrasonic beam as well. Doubling the distance results in a quarter of the energy. The beam spread is very hard to accurately describe as it depends on both material and transducer parameters, however using equation 2.9, a theoretical approximation of the -6 dB edge can be obtained, [21]. Here  $\theta$  is the conical angle,  $\lambda$  the wavelength and  $D$  the transducer diameter.

$$\sin\left(\frac{\theta}{2}\right) = \frac{0.56\lambda}{D} \quad (2.9)$$

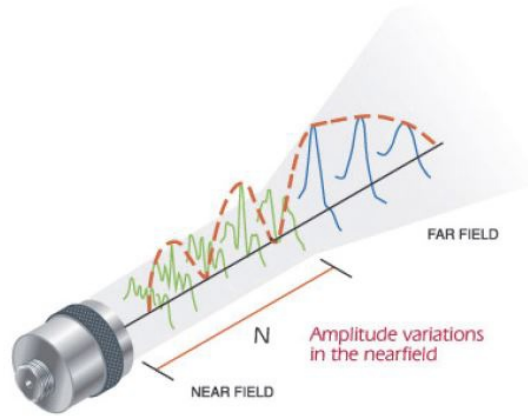
#### Interference Effects

The transducer is not a perfect point source, but has a certain dimension, usually a circular disk or a rectangle. By applying Huygens' principle the interference effects can be understood. The superposition of the waves from two (or more) point sources results in constructive or destructive interference depending on the phase alignment of the waves. The parts of the point waves that are in phase will interfere constructively and eventually form a parallel beam front (with a certain beam spread). The parts of the waves out of phase will interfere destructively. Close to the probe interference effects are most prominent before the beam has had time to stabilize, and is called the near field, NF, described by equation 2.10.  $D$  is the diameter of a circular probe. [21]

$$NF = \frac{D^2}{4\lambda} \quad (2.10)$$

Beyond the near field, after the constructive and destructive interference have stabilized, the *far field* starts. A defect in the near field may be harder to detect due to this interference depending on position of the defect, since the intensity of the sound fluctuates.

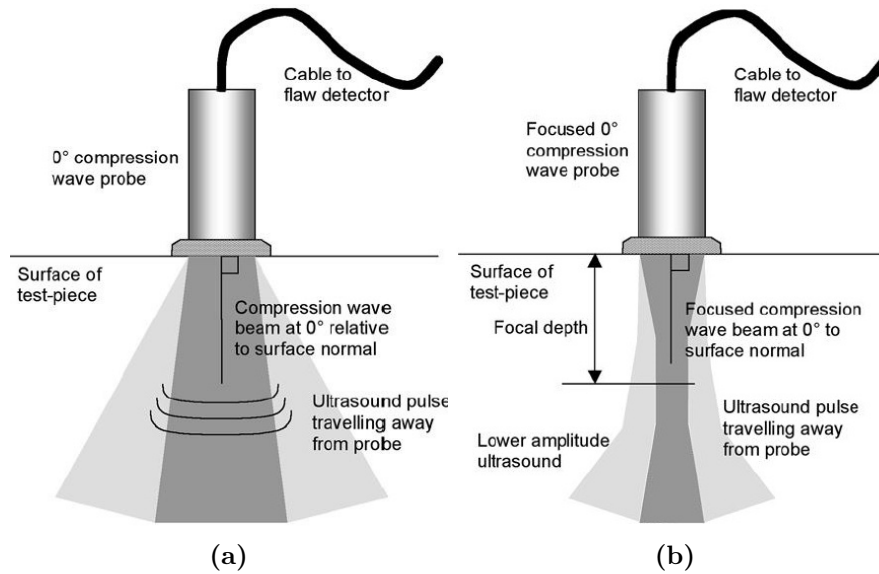
Figure 2.7 shows beam intensity as a function of distance. The interference effects can be clearly seen in the fluctuations in amplitude in the near field. Outside, in the far field, the fluctuations stop and the amplitude falls according to the inverse square law due to the beam spread with the addition of absorption and scattering.



**Figure 2.7:** The interference effects in the near field and the inverse square law in the far field. [9]

### 2.1.7 Focusing

Beam spread has a negative impact on the inspection sensitivity, where the sound energy is dispersed conically as shown in figure 2.8(a). However, using Huygens principle, shaping the transducer parabolic one can make the sound converge at a certain distance from the probe as shown in figure 2.8(b), maximizing the energy in that area. Described in section 2.1.4, the more energy at the defect, the stronger the returning signal. Since machining the transducer is permanent, a conventional focused probe can only be used in situations where the focus depth is matched to the test object.



**Figure 2.8:** (a) A conical beam from a conventional ultrasonic probe. (b) A focused beam from a conventional ultrasonic probe with parabolic transducer. [10]

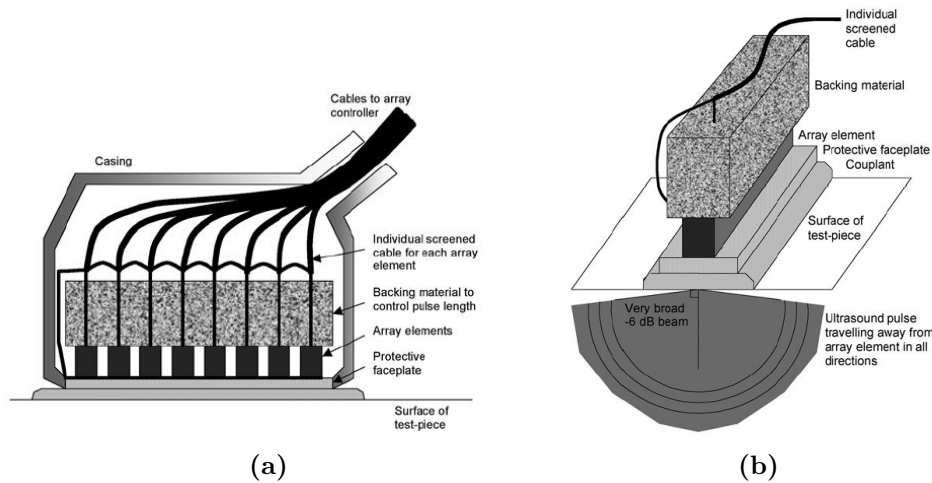
## 2.2 Phased Array Ultrasonic Testing

The phased array probe basically consist of many small conventional ultrasonic probes packed in an array as shown in figure 2.9(a). The most common type is the linear array (1-D) which consist of several rectangular elements packed together with the long side towards each other. The small

elements are individually controlled to cooperate in the inspection by a control unit, enabling electronic beam steering, focusing and scanning which make the phased array (PA) system very versatile [22, 23].

A single array element is shown in Figure 2.9(b) with typical dimensions:  $\approx 10$  mm long and  $\approx 0.5$  mm wide. The element in the array can be considered to be very small in one direction and large in the other and thus acts as a line source of sound. By packing many of these elements together the sound waves from each individual element will interact with the others according to Huygens Principle, forming a single wave front, [17].

PAUT can be used in most of the fields where conventional ultrasonic testing is used including aerospace, manufacturing, pipeline construction and maintenance, nuclear industry and more. Using one PA probe, scans in multiple angles at several focusing depths can greatly enhance detection probability and can cover a larger area of the inspection sample without moving the probe. Complex geometries of the sample can cause problems when mechanical scanning is not possible, but with a carefully chosen PA probe and simulation of the beam dynamics it might be possible to get complete coverage, [24]. Sizing of defects can be improved using electrical scanning of the beam as well as focusing of the beam which improves signal-to-noise ratio. [9, 10, 25]

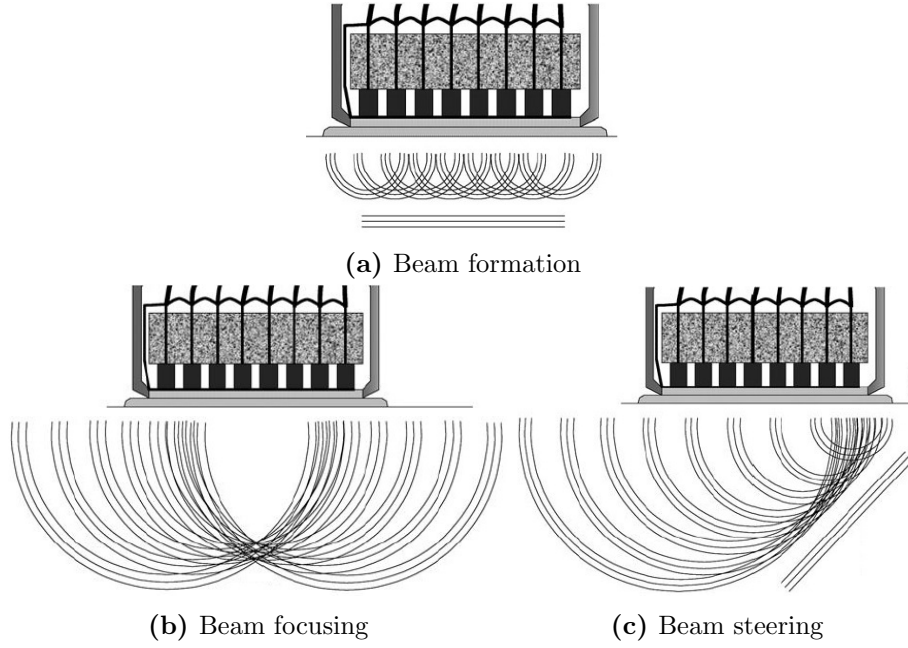


**Figure 2.9:** Example of a phased array probe layout. (a) Cross-section of a phased array probe. (b) Single element. [10]

### 2.2.1 Beam Steering and Focusing

The main advantage of the phased array system is the ability to electrically steer and focus the sound beam, i.e. phasing, and is performed using time delays. Each individual element is activated at a slightly different time relative to the others. The set of time delays is commonly referred to as a focal law which is calculated by a software.

Figure 2.10(a) show how the cylindrical waves from each element interacts in constructive and destructive interference to form a uniform wave-front. Focusing is performed by time delays that simulate a parabolic conventional probe as illustrated in figure 2.10(b). Steering uses a time delays such that the constructive interference occurs in a "side-ways" direction, resulting beam that propagate with an angle as illustrated in figure 2.10(c). It is possible to combine focusing and steering in a more complicated focal law to have a focus point at different angles. [9]



**Figure 2.10:** Beam formation of a phased array probe. (a) Superposition of point sources into a single beam front. (b) and (c) show how focusing and steering is achieved. [10]

The near field length, NF, of an unfocused PA probe sets the maximum focus length. Since a phased array probe usually consist of rectangular elements, the near field equation has to be modified as equation 2.11, where  $k$  is the aspect ratio of the element length and width according to the list below and  $L$  is the total length of the probe aperture.

$$NF = \frac{kL^2}{4\lambda} = \frac{kL^2 f}{4v} \quad (2.11)$$

| Ratio $\frac{\text{width}}{\text{length}}$ | $k$  |
|--------------------------------------------|------|
| 1.0                                        | 1.37 |
| 0.9                                        | 1.25 |
| 0.8                                        | 1.15 |
| 0.7                                        | 1.09 |
| 0.6                                        | 1.04 |
| 0.5                                        | 1.01 |
| 0.4                                        | 1.00 |
| $\leq 0.3$                                 | 0.99 |

Beam steering and focusing capabilities of the probe is affected by (mainly) four parameters: *frequency, element size, number of elements* and *pitch and aperture*.

The frequency affects the near field length, sound penetration and detectability as described before. The size of the element affects how well it simulates a line source where a thinner element enables better steering. The number of elements affect over all performance including steering and focusing, but must be balanced with complexity and cost of the total system. Pitch is the distance between elements and should be small while the aperture, i.e. the size of the active area, should be large for a large coverage. [9]

Equation 2.12 describe the beam steering capability,  $\theta_{st}$ , of the PA probe which is determined by the width of the elements,  $e$ . A thinner element simulate a better line source of sound.

$$\sin(\theta_{st}) = 0.514 \frac{\lambda}{e} \quad (2.12)$$

The versatility of the phased array probe enables the user to scan an area much faster than with conventional probes. By using a sequence of time delays in the focal law, refracted angles in the sample from e.g. 40°- 80° at an increment of 1° can be scanned simultaneously. And every angle can have a different focus depth for maximum energy at the desired position. Compare with the conventional probe which can scan only one angle at one focus depth.

### 2.2.2 Attenuation and Beam Spread

The sources of attenuation of the ultrasonic beam is the same for the phased array system as for a conventional probe. However the beam spread for rectangular elements depend on the length and width of the element and is described by equation 2.13. In the active steering plane, the elements are very small and therefore give a large beam spread, which is a wanted feature for electronic steering. In the inactive plane however, the beam spread is small due to the relatively long elements which is also a wanted feature! [9]

If the element width is too small, equation 2.13 becomes invalid, but the element will imitate a line source even better, which implies the beam spread is 180°.

$$\sin \frac{\theta_{b.sp}}{2} = \frac{0.44\lambda}{L} \quad (2.13)$$

The width of the wave front in the inactive plane is considered approximately constant due to the relatively long elements. Some beam spread occurs even for the long side of the element as seen in equation 2.14, but much less than for the short side of the element, equation 2.15. The element dimensions were taken as  $L_{long} = 10$  mm and  $L_{short} = 0.5$  mm. Here  $\lambda = c/f = 1.45$  mm for stainless steel ( $c = 5800$  m/s) and using a 4 MHz probe.

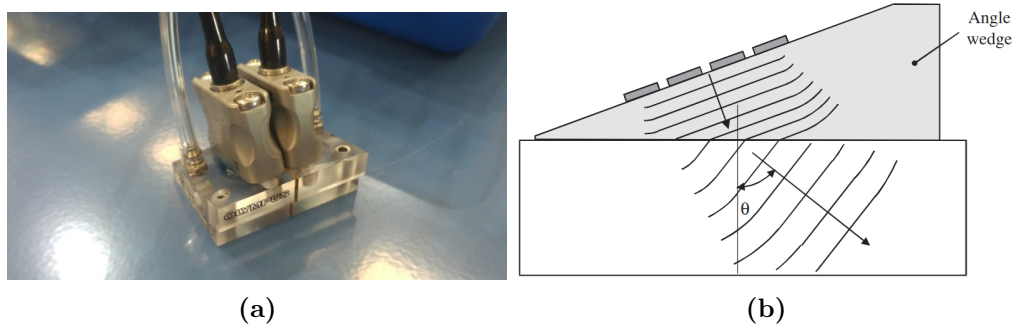
$$\sin \frac{\theta_{b.sp}}{2} = \frac{0.44\lambda}{L_{long}} = \frac{0.44 * 1.45}{10} = 0.0638 \longrightarrow \theta_{b.sp} = 7.32^\circ \quad (2.14)$$

$$\sin \frac{\theta_{b.sp}}{2} = \frac{0.44\lambda}{L_{short}} = \frac{0.44 * 1.45}{0.5} = 1.2760 \longrightarrow \theta_{b.sp} = 180^\circ \quad (2.15)$$

### 2.2.3 Wedge

In many cases, especially for weld inspection, there is a need to use high angles, typically 40° to 90°. Since the steering capabilities of a phased array system is limited, it poses a problem for many applications. By mounting the probe on a wedge one can set a mechanical starting angle from where the beam steering is offset to, illustrated in figure 2.11(b). When the probe is operated without steering there is a relatively large angle of the sound in the test piece. From this new "zero" angle a range of e.g. 30° to 90° is possible. In addition the wedge acts as a protection for the sensitive probe surface from wear during the inspections.

Since the wedge is used for guiding the sound beam it is critical that the wedge parameters, e.g. geometry and speed of sound, are known so that the software know how to calculate the focal laws. For best results and best signal to noise ratio it is important that as much sound energy is coupled into the test piece. The wedge should therefore have a very low attenuation and couple well to the test piece, a common material is the plastic rexolite.



**Figure 2.11:** (a) Example of a wedge, here with a probe (transmitter and receiver) mounted on top. (b) Illustration of the beam offset due to the angled wedge. [22]

### 2.2.4 Creeping Waves

Creeping waves can be seen as longitudinal compression waves that are refracted at very high angles, above  $70^\circ$  to  $80^\circ$ , and propagate close to the surface of the test piece. They can therefore successfully be used for sensitive detection of near surface defects. As the beam propagates, parts of the compression waves comes across the metal-air interface and thus continuously produce mode-converted shear waves, and can only be used for short distances. [26, 27]

Phased array probes that steer a beam above approximately  $70^\circ$  to  $80^\circ$  (using a wedge) will therefore produce creeping waves. Because of the additional mode converted shear waves, a larger number of reflected signals will most likely be received which can introduce interpretation difficulties. However, since the creeping waves travel with the same speed as the longitudinal compression waves, and shear waves travel with around half that speed, the signals from the creeping waves can often be distinguished.

## 2.3 316LN Austenitic Stainless Steel

The half shell cylinders that encloses the 11 T dipole magnets are produced from 316LN austenitic stainless steel. Typical 316LN austenitic stainless steel material has an equiaxed homogeneous grain structure, i.e. the shape of the grains. It has fairly small grains and no other phases or segregations. A chemical composition with large concentrations of Cr (16%-18%) and Ni (10%-14%) alloyed with Fe form a stable austenitic phase in the 316 type stainless steel. Other alloying elements are also used, and traces of unwanted elements will be present that cannot be completely removed. [28]

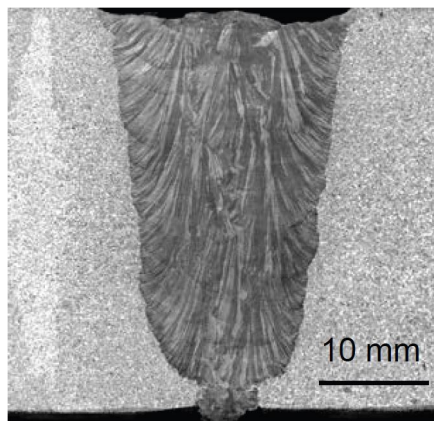
The addition of N and Mo among others to a stainless steel Fe-Cr-Ni system, will further stabilize the austenitic phase,  $\gamma$ , such that precipitation of ferrite and martensite phase can be fully eliminated. "Nitrogen increases austenite stability against martensitic transformations and is a powerful austenite former with respect to ferrite. Nitrogen substantially increases strength, while allowing ductility to be maintained down to cryogenic temperatures". [29]

The completely austenitic phase of the half shells is required for many reason. For example, the austenitic phase is non-magnetic is therefore well suited for a magnet enclosure, and it is unlikely to crack when cooling to cryogenic temperatures. However, the process of welding in austenitic stainless steels changes the structure of the weld metal.

### 2.3.1 Grain structure of austenitic stainless steel welds

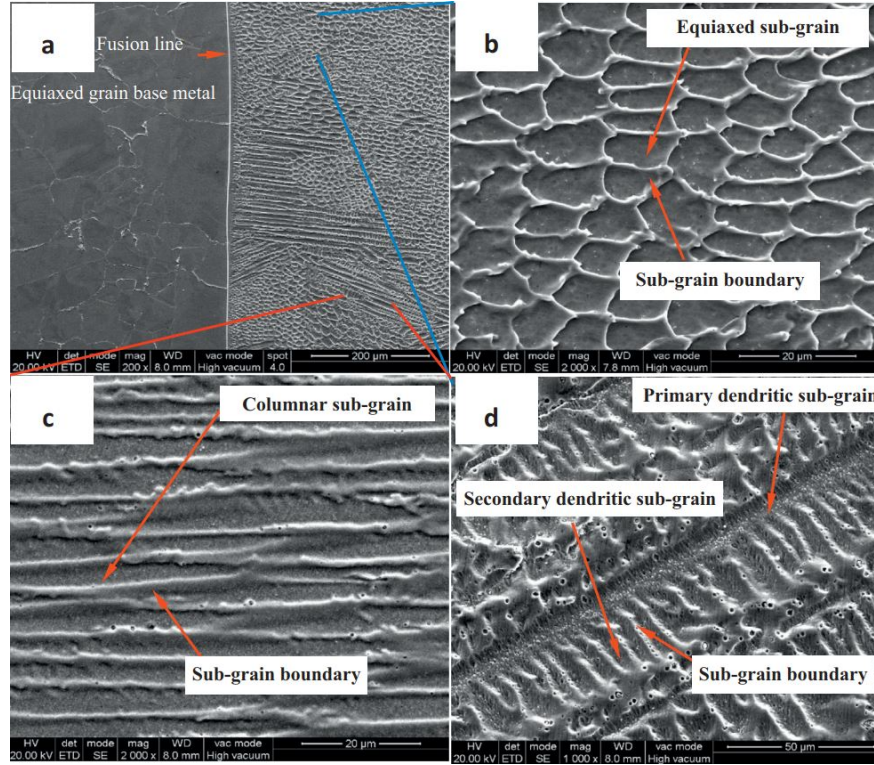
The result of welding in austenitic stainless steel depend on many variables such as welding process (Metal Inert Gas (MIG), Tungsten Inert Gas (TIG), electron beam...), choice of protection gas, heat input, additive material and welding speed to mention a few. [30, 31].

The solidification process of the melt is initially epitaxial on the grains of the base metal because of the very low nucleation barrier, the melt and solid has (almost) the same chemical composition. The high temperature of the welding process causes grain coarsening of the base metal which means that the weld is inherently coarse grained. In addition, some grains are oriented in a way that is allowing a faster solidification process and will grow at the expense of other neighbouring grains. [32] Grains up to several millimetres can be obtained [33]. Contrary to a ferritic weld, deposition of beads does not destroy the grain structure of the previous beads so the columnar grains are able to continue through the boundary of the beads. The epitaxial grain growth follows parallel to the temperature gradient which allow for an anisotropic structure as in figure 2.12. [34, 35] Sudden changes in growth direction is observed when the preferred growth direction of the grain differs too much from the temperature gradient as the weld arc moves along the weld axis.



**Figure 2.12:** Cross-section of an austenitic stainless steel weld showing anisotropic columnar growth of large grains. Grain growth direction is parallel to heat deposition. [34]

The grains of the 316LN austenitic stainless steel weld material has a sub-grain microstructure which the parent material do not, shown in figure 2.13. Equiaxed, columnar and dendritic sub-grain structures is obtained [36]. The phase is still homogeneously austenitic, however an increased amount of Cr and Mo is found in the sub-grain boundaries which induce lattice disorders such as dislocations. [37]



**Figure 2.13:** (a) SEM image showing the difference between the parent and weld metal of a 316LN austenitic stainless steel. (b) SEM image showing equiaxed sub-grain structure. (c) SEM image showing columnar sub-grain structure. (d) SEM image showing dendritic sub-grain structure. [36]

### 2.3.2 Precipitation of Other Phases in the Weld

In the weld solidification process the chemical composition of the melt can vary locally which can result in precipitation of other phases than the face-centred-cubic, FCC,  $\gamma$ -austenite. [32] Body-centred-cubic, BCC,  $\delta$ -ferrite has been observed to precipitate in between the  $\gamma$  dendrites in 316 stainless steel, although in very small amounts. The chemical composition of the parent material strongly affect the composition of the melt and will determine the amount of  $\delta$ -ferrite. For example the 304 type austenitic stainless steel is more susceptible to  $\delta$ -ferrite precipitation in comparison to the 316LN grade. [38, 39]

From  $\delta$ -ferrite islands it is common to find transformed inter-metallic  $\sigma$ -phase which is ascribed a decreased corrosion resistance and degrading mechanical properties due to its bad coherence with austenite and high interface energy. The  $\sigma$ -phase has a complex tetragonal structure and is very hard and brittle. [38, 40, 41].

### 2.3.3 Formation of Macroscopic Defects

Many types of macroscopic weld defects (size in the order of millimetres) exist and their causes is manifold making it difficult to account for the origin of all of them. Defects such as incomplete/excess root penetration, incorrect weld toe, overlap, burn through etc. (see appendix A) is

due to incorrect welding parameters such as too fast/slow welding speed, too little/much heat input and incorrect amount of addition material. [42]

### Pores and inclusions

Pores and inclusions are foreign material, gases and solids respectively, that is trapped inside the weld. While inclusions are intuitively understood as a foreign solid embedded in the weld, porosity has multiple causes.

The protection gas shields the weld from the air which otherwise will oxidise the weld melt and causing O and N to be trapped inside or react with the weld to form porosity. Each steel has an optimum shielding gas composition which produce the highest quality weld for each application. [31] Small disturbances in the flow of shielding gas such as drafts in the room, too small or too large gas flow can cause air to reach the weld. Moisture or other contaminants such as paint, grease or oil is vaporized in the high welding temperature and disturbs the weld procedure which can cause porosity.

### Cracks

316LN austenitic stainless steel has an excellent fracture resistance, but welding cause a significant decrease in the resistance due to the sub-grain boundaries of the weld metal. An anisotropic fracture behaviour has been observed, where the cracks prefer to propagate parallel to the dendritic structure [36]. Intermetallic  $\sigma$  phase embedded in the austenite matrix further weakens the weld metal and can be the source of a crack.

Hot cracks can occur where cracks form in the solidification process and propagate through the weakened weld metal [43]. In addition, thermal shrinkage during cool-down and force impacts can cause cracking.

### Lack-Of-Fusion

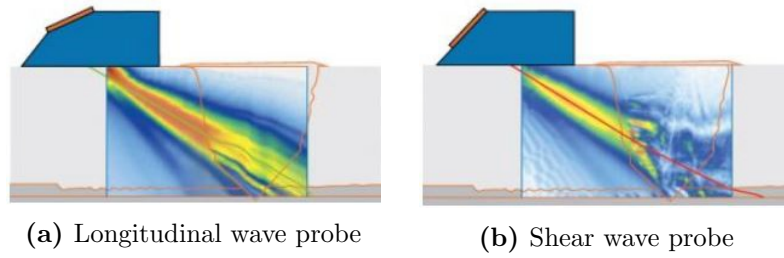
Lack-of-fusion is a part of the weld where the weld metal has not fused sufficiently to the base metal, either at the weld bevel or at the previous weld pass in a multi-pass weld. They are likely to occur when the weld arc is unable to raise the temperature to the melting point.

## 2.3.4 Sound Anisotropy and Large Attenuation of the Weld Material

The large grained, anisotropic structure with columnar grains oriented parallel to the temperature gradient has a big impact on the sound properties of the austenitic stainless steel weld metal. Shear waves have been found to be affected more than longitudinal waves, resulting in high skewing and short penetration depth as shown in figure 2.14. Therefore longitudinal waves are recommended for austenitic stainless steel. [44]

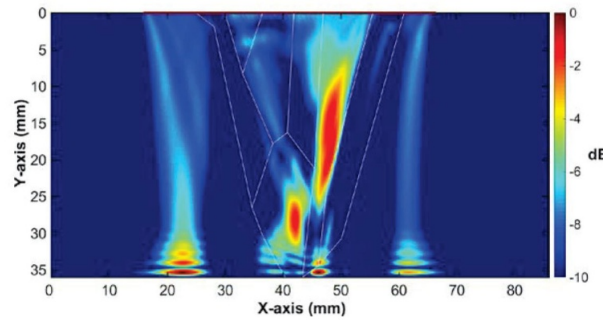
As the grains are comparably large to the wavelength of the sound, both in the order of 1 mm, the grain boundary interfaces scatters the beam for a rather large beam spread. [34] This deteriorate the signal to noise ratio because of the dispersed energy to a larger area. It also means that a larger area is covered which can cause a defect to appear in the wrong position or larger than it normally would. [35]

The size of the defects are in the millimetre scale, i.e. the same scale as the actual grain size. Luckily the defect interfaces are much more reflective than the grain interfaces, and can produce a large amplitude signal.



**Figure 2.14:** A computer model showing the difference between longitudinal (a) and shear (b) waves for 2.25 MHz waves in austenitic stainless steel. [44]

The anisotropy of the weld cause beam path deviation and splitting of the beam. Lubeigt simulated the wave propagation in a 32 mm thick 316LN austenitic stainless weld using a 2 MHz longitudinal wave, normal incidence probe, resulting in an energy distribution as shown in figure 2.15, where the probe is placed on top of the weld [45]. However, since weld inspection is usually carried out from the side of the weld cap, the energy distribution will be different because of the change in sound path towards the anisotropic weld material.



**Figure 2.15:** Simulation of the sound energy distribution in a 32 mm thick 316LN austenitic stainless steel weld. [45]

It is expected that the sub-grain boundaries of the large austenitic stainless steel grains will attenuate the sound to a larger extent compared to a grain without this sub-grain structure. The lattice disorders can possibly disturb the beam in a negative way. Small amounts of precipitates of other phases than  $\gamma$ -austenite is expected to have a similar effect. The  $\delta$ -ferrite has a slightly different speed of sound compared to austenite, which when embedded in the austenite matrix act as a mildly reflective interface. The precipitates are usually very small, and very rare in 316LN weld material so it is not expected to have significant impact.

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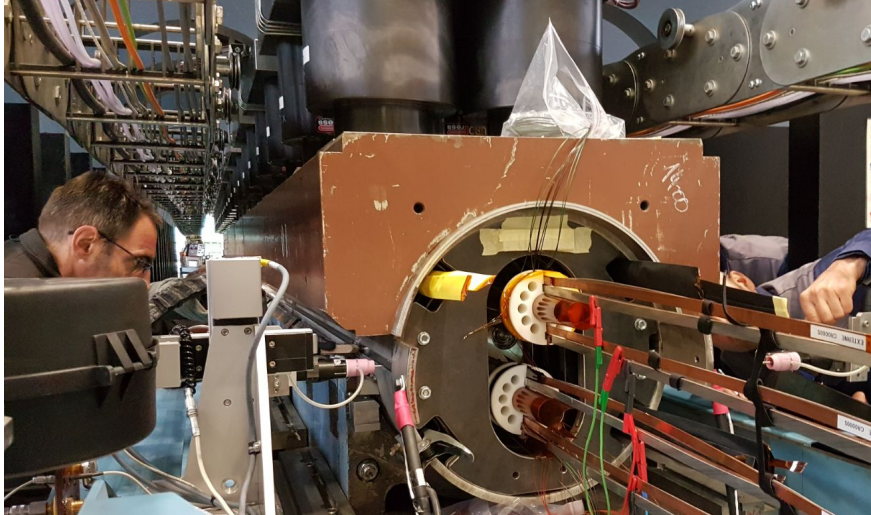
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## EXPERIMENTAL DETAILS

### 3.1 The Horizontal Welds of the 316LN Austenitic Stainless Steel Half Shells

The 5.5 m long HL-LHC 11 T dipole magnet coil assembly is closed by two 6.5 m long and 15 mm thick AISI 316LN (X2CrNiMoN17-13-3) austenitic stainless steel half shells [6] welded together under large pre-pressure in an automated horizontal weld press, shown in figure 3.1. Both sides are TIG-welded simultaneously for a total of 13 passes, each pass taking  $\approx 1$  hour, depending on weld parameters. A 30mm $\times$ 4mm backing plate placed behind the weld area keep the Ar protection gas from blowing away from the weld region when putting the first pass. After the horizontal welds are finished  $\approx 30$  cm on each sides are cut away so the weld quality is not compromised from the start and end of the weld passes.



**Figure 3.1:** Image of the welding procedure of the first 11 T dipole prototype magnet austenitic stainless steel half shells. The full magnet assembly is placed in a weld press with the pressure applied vertically and both sides of the half shells welded simultaneously.

The pre-pressure created from the weld process is needed because of the thermal cycles the magnet is subjected to when cooling the magnet from room temperature to 1.9 K and back. The different thermal expansion coefficients of the magnet components can cause parts to move inside the magnet if the pre-pressure is not large enough which will damage the sensitive superconducting

coils. In operation, the large magnetic forces created in the two 11 T magnets can damage the superconducting cables if not fixed in their permanent positions.

A high quality austenitic stainless steel enclosure is needed to ensure that the magnet has a long operation time. The weakest link is the welds which must be inspected non-destructively according to the standards of pressure vessels. [8]

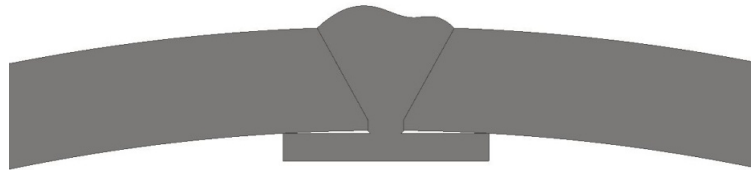
The half shells are produced by ArcelorMittal according to CERN specifications [6], and follow **AISI 316LN** or X2CrNiMoN17-13-3 according to EN 10028-7 [46] unless otherwise stated. The required chemical composition are shown in table 3.1. The physical and mechanical properties of the steel, for example thermal contraction, relative magnetic permeability, tensile strength, weldability and machinability is all affected by the composition and this steel has been calculated to comply with the application requirements.

**Table 3.1:** Chemical composition of the 316LN austenitic stainless steel half shells. Concentration by mass %. Absolute concentration is given for one shell as an example. \* CERN requirement. [6]

| Element               | Concentration, % | Limit, %                |
|-----------------------|------------------|-------------------------|
| Chromium, <b>Cr</b>   | 18.0             | *Min = 16.0; max = 18.0 |
| Nickel, <b>Ni</b>     | 12.7             | *Min = 12; max = 14.0   |
| Molybdenum, <b>Mo</b> | 2.56             | *Min = 2.00; max = 3.00 |
| Nitrogen, <b>N</b>    | 0.17             | *Min = 0.15; max = 0.20 |
| Carbon, <b>C</b>      | 0.03             | Min = -; max = 0.03     |
| Silicon, <b>Si</b>    | 0.48             | Min = -; max = 1.00     |
| Manganese, <b>Mn</b>  | 1.19             | Min = -; max = 2.00     |
| Cobalt, <b>Co</b>     | 0.02             | Min = -; max = 0.10     |
| Phosphor, <b>P</b>    | 0.016            | *Min = -; max = 0.030   |
| Sulphur, <b>S</b>     | 0.001            | *Min = -; max = 0.010   |
| Iron, <b>Fe</b>       | 65               | Remainder               |

The structure of the steel is completely homogeneous with only stable austenitic phase, no other phases or segregations. It has a relative small grain size, the ASTM grain size number is higher than 3 and homogeneous within  $\pm 1$  throughout the shell. This is equivalent to a minimum of 62 grains/mm<sup>2</sup> calculated with equation:  $N = 15.5 * 2^{G-1}$  where  $G$  is the grain size number. [47]

The half shells start of as large plates 1.100 m wide, 6.500 m long and 16 mm thick and later formed into half shells to an inner radius of 270 mm. The long edges are then cut at a 29° angle. [6] Figure 3.2 show a CAD model of the weld region. The surface finish is matt-pickled without any scratches, surface marks or other defects when delivered to CERN. However, after the welding process spatter, tack weld supports and pressure marks from the weld-press and magnet assembly may occur.



**Figure 3.2:** CAD-model of the weld geometry.

Knowing the speed of sound of the component is crucial for reproducible results since the ultrasonic software converts time difference of the ultrasonic pulse into distance. A tabulated value of 5800 m/s for stainless steel has been used in the PAUT software.

The velocity of longitudinal compression waves has been measured on two austenitic stainless steel 316LN flat plates, one 8 mm thick giving 5793 m/s, and one 16 mm thick giving 5787 m/s with an average of 5790 m/s. This value is very close to the tabulated value of 5800 m/s. The 8 mm thick plate measurement used the 2nd and the 3rd back wall echoes while the 16 mm thick plate used the 1st and 2nd back wall echoes. Courtesy to Simon Garner, EN-MME, CERN. The equipment is given in table 3.2.

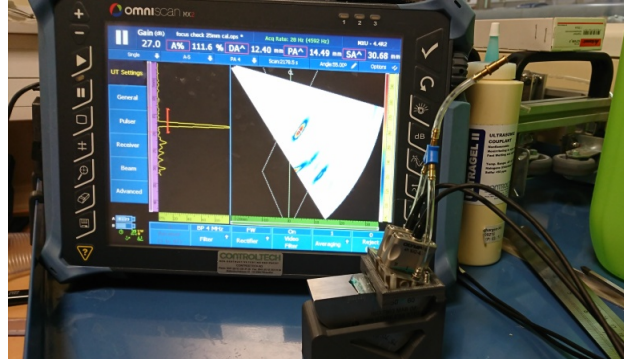
The smallest defect that can be detected by the ultrasonic equipment depends on the sound wavelength as discussed in theory, and the minimum detectable defect size is often taken half of the wavelength,  $\frac{\lambda}{2}$ , [48]. Calculating the wavelength using  $\lambda = v/f$  gives for the 4 MHz probe:  $\lambda = 1.45 \text{ mm} : \frac{\lambda}{2} = 0.725 \text{ mm}$ . However the strong attenuation and scattering of the austenitic stainless steel welds negative affects the minimum detectable size which is most likely a bit larger.

**Table 3.2:** Equipment for velocity measurements.

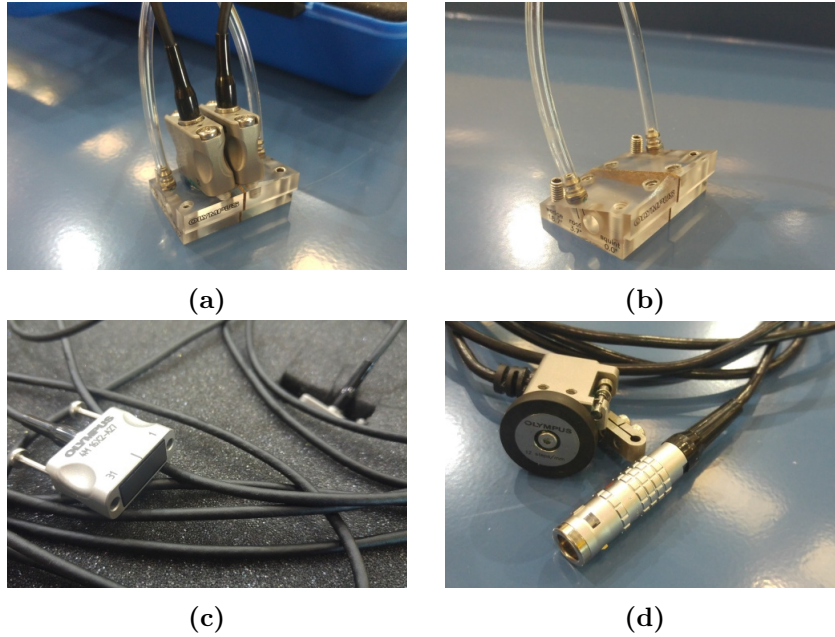
|                  |                                                 |
|------------------|-------------------------------------------------|
| Acquisition unit | Krautkramer USN 60                              |
| Probe name       | GE Alpha 2                                      |
| Probe type       | Single element longitudinal<br>compression wave |
| Frequency        | 10 MHz                                          |
| Angle            | 0°                                              |
| Element diameter | 8 mm                                            |

### 3.2 PAUT Equipment

The essential PAUT components are the acquisition unit, the probes with wedges and the encoder for position measurement. A full list of the PAUT equipment can be found in appendix B - PAUT Equipment for 11 T Dipole Weld Inspection. The PAUT unit *Omniscan MX2* from Olympus is shown in figure 3.3. The acquisition/control unit *OMNI-M2-PA 32:128PR* capable of simultaneous and individual control of 32 elements, with support for 128 channels. A splitter, *Omni-A2-SPLIT128*, is used to be able to connect two probes for a two side inspection set-up. The longitudinal 4 MHz Dual-Matrix-Array, DMA, probes Olympus DMA-4M-16X2-A27 that are shown in figure 3.4(c), contain a transmitter and a receiver in separate housings. The longitudinal DMA wedges SA27-DN55L-FD15-IHC, (figure 3.4(b)), have a sound insulating barrier in the middle so that the transmitter and receiver probes are acoustically insulated, which minimizes the acoustic feedback. The Olympus Mini-Wheel encoder, (figure 3.4(d)), is capable of recording 12 steps/mm.



**Figure 3.3:** Omniscan MX2 acquisition unit.



**Figure 3.4:** (a) Probe and wedge assembly. (b) Wedge Olympus SA27-DN55L-FD15-IHC, (c) dual matrix array probes Olympus DMA-4M-16X2-A27 and (d) encoder for PAUT testing of the 11 T dipole shells.

The 4 MHz longitudinal wave dual matrix probes DMA-4M-16X2-A27 have been selected because of their good penetration depth in large grained austenitic stainless steel welds and their relatively good sensitivity for small sized defects. The splitting of the probe into one transmitter and one receiver, called the transmit-receive longitudinal (TRL) technique, gives an improved signal to noise ratio. "These probes eliminate the interface echo, have no dead zones due to wedge echoes, reduce the backscattering signals and permit the use of higher gain", [49]. The TRL technique is especially used for acoustically noisy materials such as austenitic stainless steel welds and dissimilar weld material.

Wedges with an  $18.7^\circ$  wedge angle are used in order to offset the beam to around  $55^\circ$  in the steel material, as described in the theory section (figure 2.11(b)), so that it can enter the weld region. With the additional mechanical  $55^\circ$  offset, the electronic beam steering can reach angles between approximately  $30^\circ$  to  $85^\circ$ . The wedges are custom made for the TRL DMA probes with a sound insulating barrier to isolate the transmitter from the receiver parts. The two probe housings are then placed on the wedge which has a small roof angle that creates a pseudo-focused beam, i.e. the receiver is only sensitive for signals from a limited volume where two beams from the transmitter and receiver overlap as shown in figure 3.5. [44]

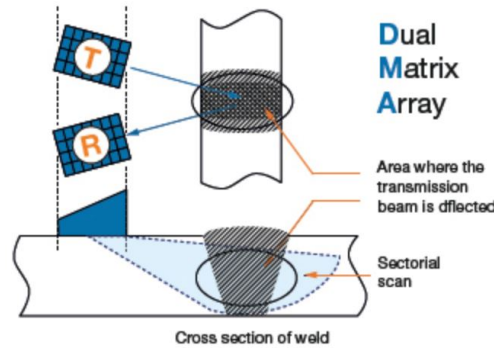


Figure 3.5: The TRL technique. [44]

**Probe: DMA-4M-16X2-A27**

- Dual matrix array, DMA
- Longitudinal waves
- Frequency: 4MHz
- Element count: 64
- Active area: Length 16 mm, elevation 6 mm
- Primary pitch: 1.0 mm
- Secondary pitch: 3.0 mm
- Matching medium: Rexolite

**Wedge: SA27-DN55L-FD15-IHC**

- Longitudinal DMA wedge
- Wedge angle:  $18.7^\circ$
- Roof angle:  $3.7^\circ$
- Material: Rexolite
- Nominal beam angle:  $55^\circ$
- Bottom surface: Flat
- Irrigation ports for water couplant
- Carbides for wear protection

For the active area,  $16 \text{ mm} \times 6 \text{ mm}$ , and the width of the element,  $\approx 1 \text{ mm}$ , the near field distance is:  $N = \frac{0.99 \cdot 16^2}{4 \cdot 1.45} \approx 44 \text{ mm}$  using equation 2.11 with aspect ratio  $k = 0.99$  and  $\lambda = \frac{c}{f} = \frac{5800 \text{ m/s}}{4 \text{ MHz}} = 1.45 \text{ mm}$

The beam steering capability is:  $\theta_{st} = \arcsin\left(0.514 \cdot \frac{1.45}{1}\right) \approx 48.2^\circ$  using equation 2.12

Beam spread in the inactive plane of the probe is calculated using equation 2.13:

$$\theta_{b.sp} = 2 * \arcsin\left(\frac{0.44 \cdot 1.45}{6}\right) \approx 12.2^\circ$$

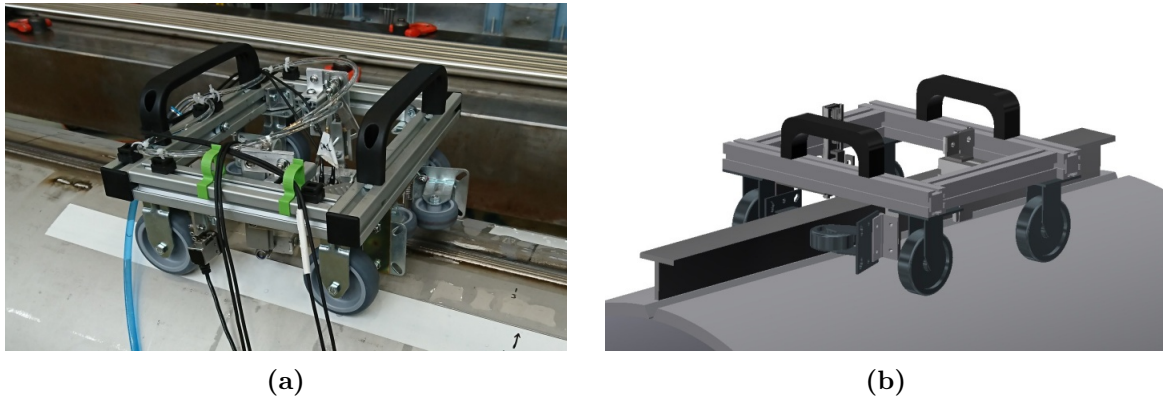
The encoder *Mini-Wheel* shown in figure 3.4(d), from Olympus is connected to the Omniscan to synchronize the probe movement with data acquisition in the scan axis at 12 steps/mm. This enables the user to position and dimension indications found in the weld. The encoder attachment

is spring loaded to keep it in contact with the rolling surface at all times.

A couplant feed unit from Olympus, *CFU05*, was acquired to supply water couplant to the wedges. The pump is a diaphragm type to avoid priming problems and has a bypass to ensure constant water flow. The maximum flow capacity is 3.78 L/min, and adjustable through a control valve. The water inlet tube is equipped with a check valve to make sure it is always filled, an algae filter and a debris filter. [50]

### 3.3 Manual Scanner for Ultrasonic Testing of the Long Horizontal Welds of the 11 T dipole

A mechanical scanner for PAUT testing of the horizontal welds of the 11 T dipole half shells has been developed and was produced in the Large Magnet Facility (LMF) workshop at CERN. Figure 3.6(a) shows the scanner placed on top of the first 11 T dipole prototype magnet. Figure 3.6(b) show a CAD assembly of the scanner.



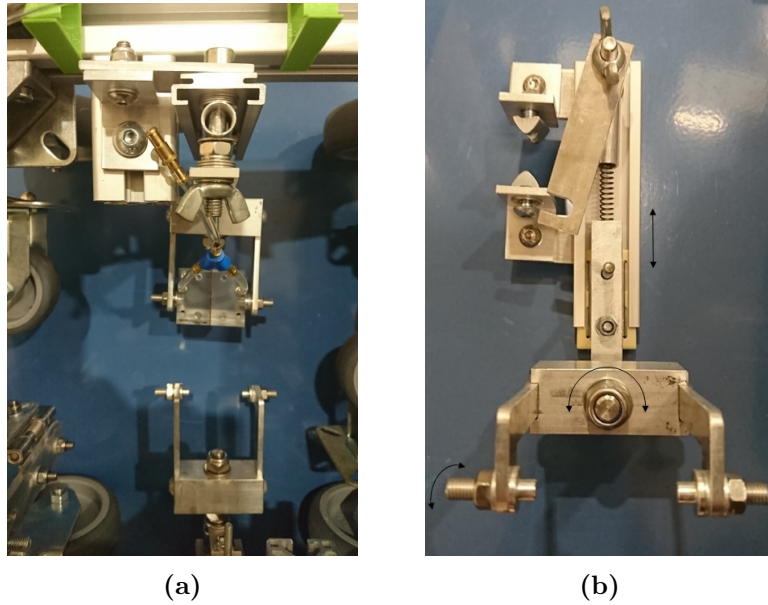
**Figure 3.6:** (a) 11 T dipole prototype magnet weld with PAUT set-up. (b) CAD assembly of the scanner on top of magnet half shells. A mounted T-bar is also shown.

The scanner allows to guide two DMA probes along either side of the weld. An alignment system, two adjustable wedge holders, a length position encoder, coupling water supply and cable holders are integrated in the scanner for easier operation.

The frame was built with aluminium profiles for good mechanical stability and offers to add parts in the future. The wheels, handles, hinges, tubes and other small parts were bought off the shelf. Custom parts, e.g. the wedge holders, were produced in-house.

The scanner is aligned to the weld by a T-bar that is mounted on top of the weld using specially designed T-bar holders and clamps see appendix B, figure B.1. Four wheels, two on each side with rolling direction in the horizontal plane is pressing towards the T-bar with spring loaded hinges as shown in figure 3.6(b). This means that the probes will have a constant distance to the T-bar at all times.

The wedges are mounted on spring loaded linear gliders to keep the wedge pressed to the half shell surface during the entire scan, shown in figure 3.7. The wedge holders have multiple degrees of freedom in order to align probe height, vertical distance and angle with respect to the weld.



**Figure 3.7:** (a) Top view of the wedge holder with mounted wedge. (b) Front view of the wedge holder. Arrows show axis of motion.

### 3.4 Calibration of the PAUT Set-Up

The primary purpose of the PAUT set-up calibration is to be able to draw quantitative conclusions of the position, the size and the type of defects that are causing an echo in the PAUT inspection data. By using dedicated calibration blocks with different artificial defects, the gain of the reflected signal can be adjusted in a way that same sized defects give a similar response independent of defect location.

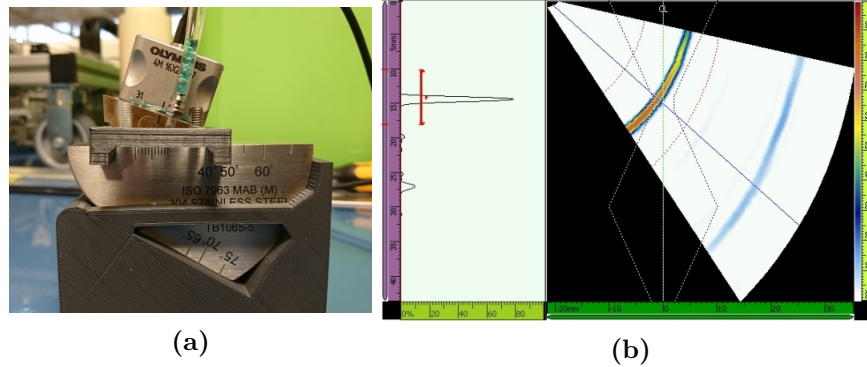
#### 3.4.1 Range Calibration

Before range calibration the beam exit point from the wedge must be determined. The beam exit point is defined as the point on the bottom of the wedge where the most energy exits the wedge, i.e. at the centre of the beam. A phased array probe has a range of beam exit points, approximately 2 mm, depending on the different angles of the beams. In this note the  $55^\circ$  beam was chosen for determining beam exit point since this is the wedge offset angle.

Calibration block No 2 (figure 3.8(a)) has been used for beam exit point and range calibration as described in *ISO 7963 - Welds in steel - Calibration block No. 2 for ultrasonic examination of welds* [52]. The beam exit point for the  $55^\circ$  beam is found by placing the probe facing the 25 mm radius and maximizing the signal from the (1st) back wall echo shown in figure 3.8(b). Section 3.7 describes how to interpret the data in figure 3.8(b). The exit of the centre of the beam energy now coincide with the centre of the 25 mm radius back wall. The sound path distance measured by the instrument should show 25 mm, although that is rarely the case before calibration. Small differences in wedge dimensions will show up as range deviations. Therefore a wedge delay is manually set until the echo align with 25mm.

The echoes in the angular range deviate slightly from the 25 mm sound path as shown in figure 3.8(b). This is because of the different beam exit points for higher and lower angle beams. By applying an angle dependent wedge delay, more for large angles and less for low angles the PAUT equipment can compensate for the different beam exit points so all angles show  $25 \pm 1$  mm sound path.

To control the quality of the range calibration a measurement on the 50 mm radius on block No. 2 shall be performed routinely before starting the 11 T dipole weld inspection. Measuring on other austenitic stainless steel blocks with known artificial defects can be used to verify the calibration as well.



**Figure 3.8:** (a) Probe and wedge positioned on the calibration block No. 2. (b) A- and S-scan of the back wall echo from the 25 mm radius of calibration block No. 2.

### 3.4.2 Sensitivity Calibration

Typically, two types of sensitivity calibrations are required, Angle-Corrected-Gain (ACG) and Time-Corrected-Gain (TCG). The ACG is very important and will determine detectability and sizing of defects. TCG on the other hand is not required in this project because the sound path distances to the areas of interest in the relatively thin 15 mm half shell welds are similar, between 20 and 30 mm. Therefore, unless explicitly mentioned, all PAUT results presented in this note have been acquired with ACG but not with TCG.

Two defects of the same type, size and distance to the beam exit point will not give the same amplitude response depending on the needed beam angle to reach them. The increased beam spread, mode conversion, attenuation and scattering associated with high angle beams result in a weak signal. The ACG apply an angle dependent gain to bring the signals of defects of the same size and type from all angles to the same amplitude.

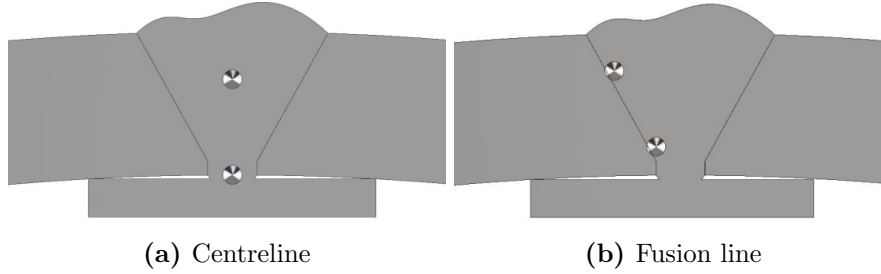
An ACG can be constructed by two different methods. One method is by directly adjusting the gain while measuring on a block with a radius, like on calibration block No.2. The amplitude recorded for each angle is corrected by the machine to show e.g. 80% full-screen-height, FSH.

The other method is by recording the amplitude from two or three artificial defects at the same sound path but reached by different angled beams. The signals received from these defects are corrected to show e.g. 80% FSH. Based on the corrected gain for these two or three angles the machine extrapolates a correction gain for all other angles.

The last method offers more flexibility. The choice of artificial defect type and size will affect the calibration. A good representative calibration is obtained with a block with artificial defects produced from a weld material. The best calibration is obtained if the block is an exact replica of the material intended for the inspection. Therefore, calibration blocks has been produced from the cut-off end welds of the 11 T dipole prototype magnet.

The highly attenuating and anisotropic austenitic stainless steel weld material and the curved shell surface of the 11 T dipole magnet will affect the ultrasonic beam propagation in an often unexpected manner. By machining side-drilled-holes (SDHs) in the weld material these can be used to directly measure the received amplitudes and that way estimate the ultrasonic properties for the ACG. A CAD model of a weld sample with SDHs in the weld centreline is shown in figure 3.9(a) and a reference sample with SDHs in the fusion line is shown in figure 3.9(b). Similar

weld samples with notches in the surfaces, flat-bottomed-holes (FBHs) drilled to the fusion line and SDHs at different positions can be used as references for sizing and positioning of defects.

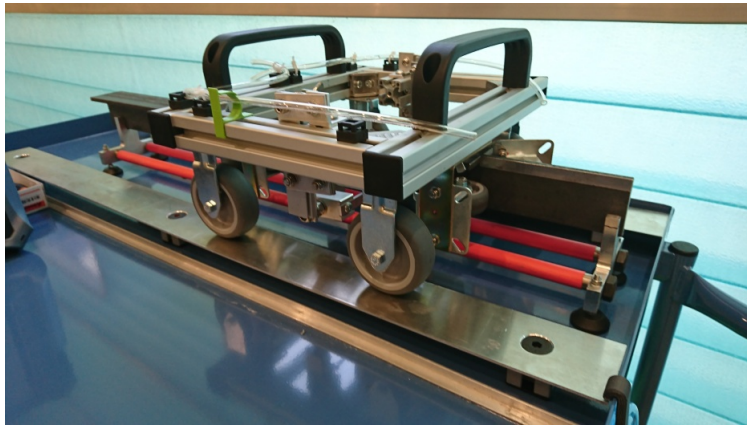


**Figure 3.9:** (a) CAD model of a sample with centreline SDHs. (b) CAD model of a sample with fusion line SDHs.

### 3.4.3 Calibration Station

A good calibration of the ultrasonic testing system is needed for a quantitative defect analysis. Again, the mechanical stability and position of the probes in regard to the weld of the blocks are of highest importance. As described in ISO 17640 [13] the system must be calibrated before and after every test and if any changes in configuration is made. Therefore, the calibration station shown in figure 3.10 was designed and produced to facilitate routine sensitivity calibrations prior to the 11 T dipole weld inspections.

The purpose of the station is to simulate the magnet inspection while using calibration blocks with known and defined artificial defects. The blocks are placed on the red rubber covered tubes and aligned to the T-bar. After calibration the probe and wedges can remain mounted in the scanner while it is removed. This way the probe-weld distance and probe angle in relation to the weld can be maintained for representative calibration.



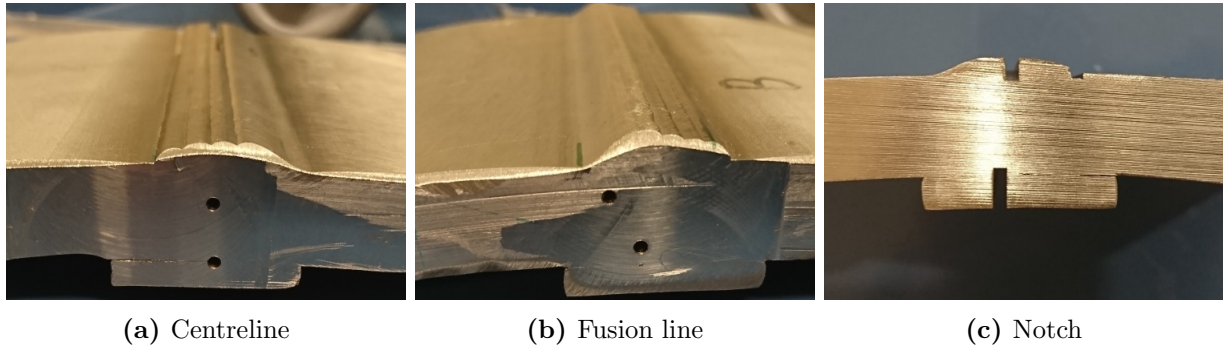
**Figure 3.10:** The calibration station with scanner. The calibration blocks are placed on the red tubes, the T-bar is used to align the scanner to the welds of the samples. The rails keep the scanner in the correct height position.

### 3.4.4 Stainless Steel Welds from 11 T Dipole with Artificial Defects for Calibration and Reference measurements

From the 15 mm thick 316LN austenitic stainless steel half shell welds that were cut from the extending ends of the first 11 T dipole prototype magnet half shells, four representative calibration and reference samples with artificial defects could be produced. Their design follow ISO 22825 [14].

In order to exclude the presence of large natural defects, and to confirm the position of the artificial defects (SDHs, FBHs and notches), the weld samples were examined by radiography, which did not reveal any natural defects.

For sensitivity ACG calibration of the PAUT equipment,  $\varnothing=2\text{mm}$  SDHs in the weld centre are used (figure 3.11(a)). Additional reference welds with artificial defects were used to verify the detectability of different defect types. The weld with  $\varnothing=2\text{ mm}$  SDHs at the weld fusion line (figure 3.11(b)) represents defects at the fusion line. A weld with notches in the top and bottom surface (figure 3.11(c)) is used to simulate surface/near surface defects and root cracks. The 2 mm wide notches are machined to a depth of 1 mm below the original half shell surface, e.g. the bottom notch is 6 mm deep since the backing plate is 5 mm thick.

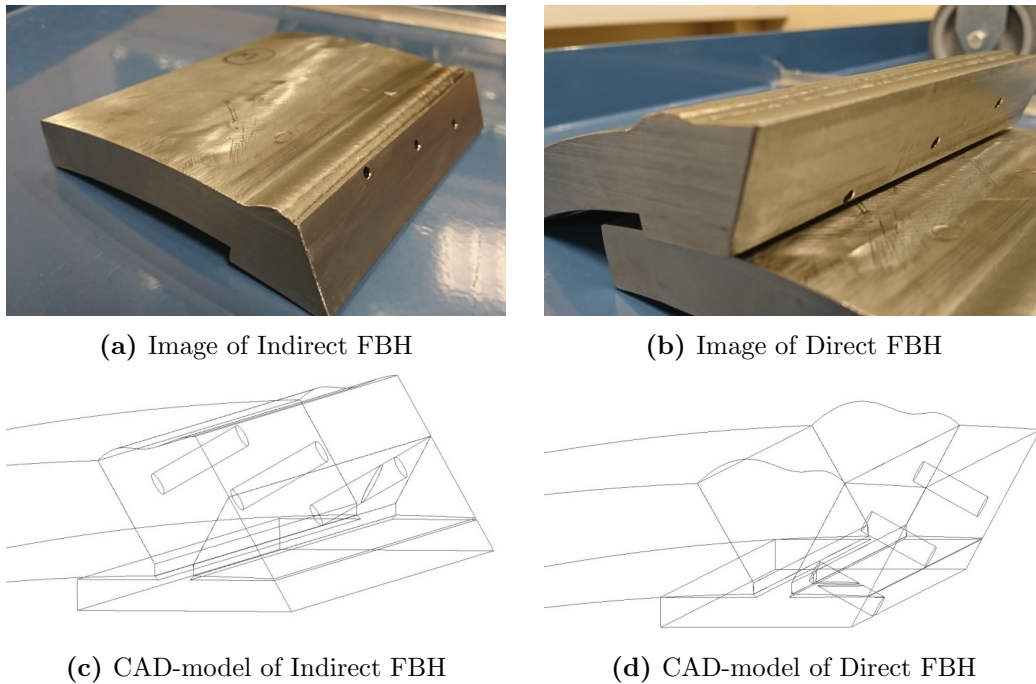


**Figure 3.11:** (a) Picture of the calibration block with 2 mm diameter centreline SDHs. (b) Picture of the calibration block with 2 mm diameter fusion line SDHs. (c) Picture of the block with 1 mm deep notches from the shell surface.

The SDHs simulate volume defects such as pores or inclusions which have a significant size in all direction and thus reflects sound such that an echo is obtained independent on the beam incidence angle. The width of the ultrasonic beam is approximately 6 mm, the same width as the elements in the probe. Volume defects longer than approximately 6 mm will produce an echo from the total width of the beam. However defects smaller than 6 mm will not and therefore, smaller echoes are received from these.

Welds with 3 mm diameter flat-bottomed-holes (FBH), which were drilled to the weld bevel at three different heights, simulate flat defects such as lack of fusion and cracks. These are two of the most important types of defects to detect and characterize.

The FBHs in the weld sample shown in figure 3.12(a) are detected *indirectly* because the orientation of the holes reflect the sound downwards. The beam is then reflected on the bottom surface before reaching back to the probe. The FBHs in the weld sample shown in figure 3.12(b) can be detected *directly*, i.e. the sound beam reflects directly from the hole back to the probe. The pairs of FBHs at the same height in both blocks are identical in the sense that they simulate the exact same defect and only the probe is positioned on two different sides of the weld. Their location is 4.5 mm, 9 mm and 13 mm below top surface for the top, middle and bottom FHB respectively.



**Figure 3.12:** (a) Picture of reference weld with FBH for indirect detection. (b) Picture of reference weld with FBH for direct detection. (c) and (d) CAD model of respective weld sample. In both samples the FBHs end at the weld bevel at 4.5 mm, 9 mm and 13 mm below the outer shell surface.

### 3.5 Wedge-Surface Coupling to the Stainless Steel Shells and Required Surface Preparations

Before ultrasonic testing can begin the surfaces close to the weld must be prepared. Any spatter, marks or grooves from the weld procedure or the press can interfere with the wedge-surface coupling and can damage the wedge during scanning. Water is used as coupling medium between the wedge and magnet surface. Figure 3.13 shows typical surface features that must be removed. The tack welds must be grinded away to a smooth surface. The pressure marks however cannot be fully removed without grinding away too much base material, but the edges must be smoothened out. The same goes for spatter, marks, grooves and other that extend above surface level.



**Figure 3.13:** (a) Surface features from the weld procedure. (b) Grinded tack weld and pressure mark.

## 3.6 Software

### 3.6.1 NDT SetupBuilder

The NDT SetupBuilder 1.1 enables focal law creation and simulation of beam propagation in the sample. It has predefined settings for different probes and wedges including the DMA 4M 16x2-A27 probe and SA27-DN55L-FD15-IHC wedge for easy configuration. Dimensions of the sample can be defined, including weld geometries, however with some limitations. Curved surfaces are not supported for DMA PA probes.

Several groups (individual focal laws) can be created to scan in different probe offsets, angle intervals, focus points and/or focus geometries, e.g. true depth or half path. After creation, the focal laws are exported to an SD-card for use in the Omniscan.

### 3.6.2 Omniscan MXU 4.4

The Omniscan MXU 4.4 software in the Omniscan MX2 is used to control the probes and encoder for data acquisition and can be used for data analysis and reporting of the data. It has easy menus and wizards for fast navigation to the many settings.

### 3.6.3 OmniPC 4.4

The OmniPC 4.4 is an analysis and reporting software of saved inspection data and has the same interface as the Omniscan MXU software.

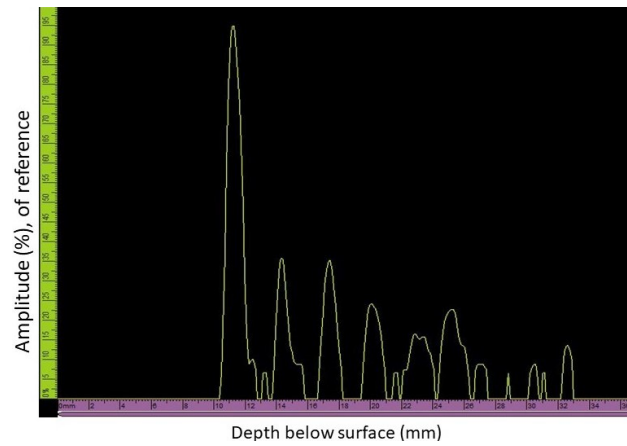
### 3.6.4 Autodesk Inventor Professional 2017

The design of all the mechanical parts, e.g. the scanner and the calibration station, was done in Autodesk Inventor Professional 2017.

## 3.7 Explanations of Views for Interpretation of PAUT data

### 3.7.1 The A-scan

The A-scan, shown in figure 3.14, is the most fundamental view and is a plot of signal amplitude in percent of a decibel (dB) reference value, versus time. If the PAUT set-up is correctly configured the A-scan can plot amplitude (%) versus depth below surface (mm). The A-scan can be used as a tool to determine the type of defect by looking the peak shape and peak size, [48, 53]

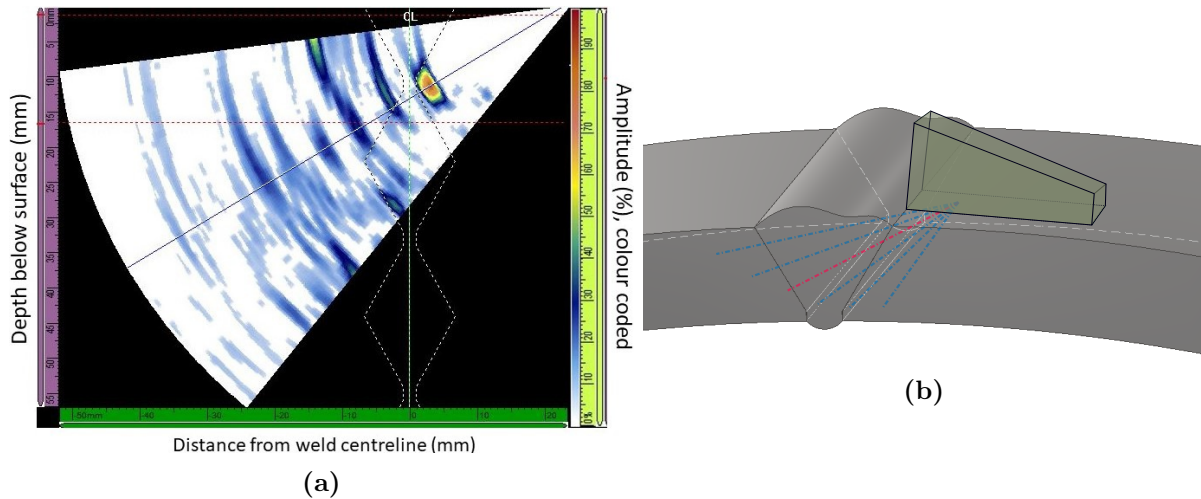


**Figure 3.14:** An example of an A-scan.

### 3.7.2 The S-scan

The S-scan is a construction of several A-scans from beams at different angles,  $\theta$ , where the software converts amplitude into colour (red for large and white/blue for small amplitudes) and plots the colours such that a coloured fan is created, shown in figure 3.15(a). The S-scan basically shows a cross-section of the weld. The long diagonal line in the S-scan constitutes one A-scan which is actually shown in figure 3.14. By rotating the diagonal line, all A-scans that constitute the S-scan can be viewed individually. Figure 3.15(b) shows an illustration of how the S-scan is constructed by individual A-scans.

In figure 3.15(a) the y-axis is depth in the material (mm) and the x-axis is distance from the centreline of the weld (mm). A weld overlay, shown as dotted black lines around the centreline of the weld, is predefined in the S-scan which facilitates the localization of found defects.



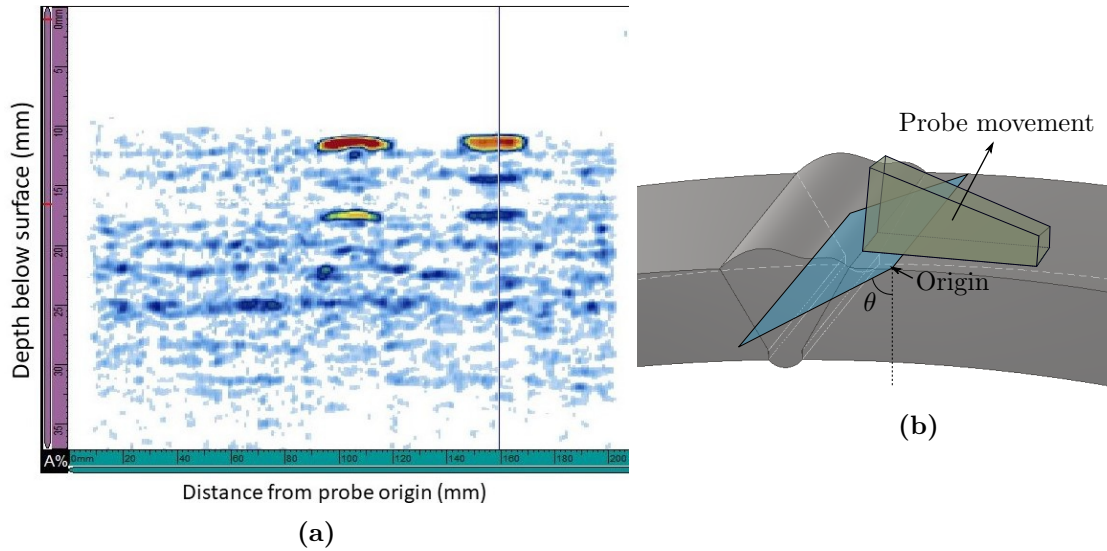
**Figure 3.15:** (a) An example of an S-scan view of measurement data. The dotted black lines in the shape of triangles mark the weld overlay. The right axis shows the colour coding of the signal amplitude. (b) Illustration of the beams of different angles to form an S-scan. The red beam illustrates one A-scan.

### 3.7.3 The B-scan

The B-scan shown in figure 3.16(a) is constructed continuously during the weld inspection by recording the measurements while moving the probe along the weld. One angle,  $\theta$ , of all of the ultrasonic beams is chosen as illustrated by the selection of a plane in figure 3.16(b). The signal amplitudes are recorded and converted into colour. The colours are then plotted in a graph with depth below the surface on the y-axis and probe length position, i.e. distance from probe origin, on the x-axis.

The B-scan basically show a cross-section of the weld when cut along the chosen plane in figure 3.16(b). The vertical line in the B-scan in figure 3.16(a) correspond to one A-scan and is actually the one shown in figure 3.14.

By choosing a different angle,  $\theta$ , i.e. a different angle of the plane in figure 3.16(b), the B-scan will change accordingly. This way, different areas of interest can be analysed individually for the entire length, or a large section of the weld.



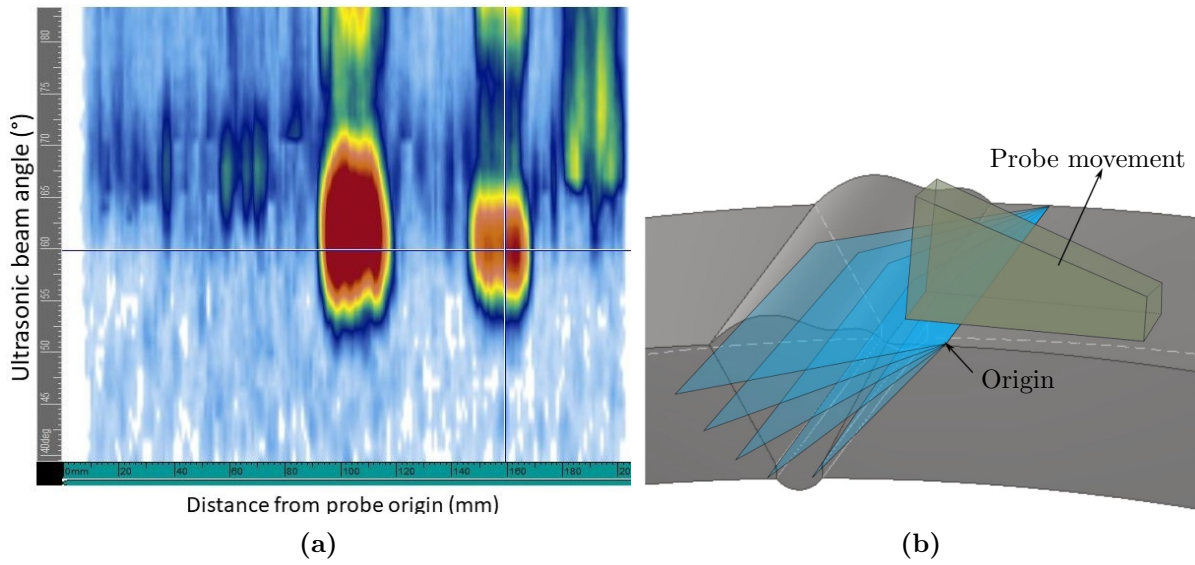
**Figure 3.16:** (a) An example of a B-scan view of measurement data, 200 mm long. The vertical line in the B-scan correspond to one A-scan. (b) Illustration of the beam selection, i.e. plane angle, for the B-scan.

### 3.7.4 The C-scan

To create the C-scan the software takes all the B-scans and compresses them into one plot and the result is shown in figure 3.17(a). The x-axis is the distance from origin, and the y-axis is the  $\theta$ -angle. In other words, each angle (horizontal line) in the C-scan correspond to one B-scan which is illustrated in figure 3.17(b).

The horizontal line in figure 3.17(b) correspond to the B-scan in figure 3.16(b).

To make the C-scan more useful, one can choose to only visualize parts of the information by placing a gate that selects only the information that was acquired from signals that travelled a certain distance. This was done for the C-scan shown in figure 3.17(a).



**Figure 3.17:** (a) An example of a C-scan view of measurement data, 200 mm long. (b) Illustration of the beam selection for the C-scan.



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# 4

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## ULTRASONIC BEAM DYNAMICS AND COMPARISON OF PAUT FOCAL LAWS

### 4.1 The Effect of Structure of the Weld Material on Ultrasonic Beam Dynamics

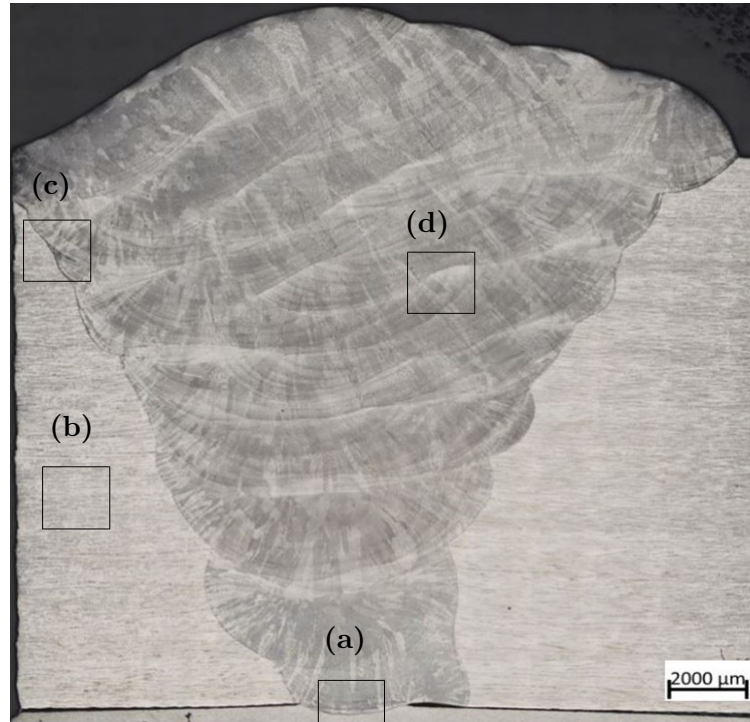
Figure 4.1 show a microscopy image of the cross-section of the 11 T dipole horizontal austenitic stainless steel weld. The surface was polished and oxalic etched. The general structure of the weld can be seen and the individual weld passes can be distinguished as dark/white "interfaces", especially clear for the first four root passes. A clear difference between weld metal and parent metal is observed where the weld metal is rather rough and disordered while the parent metal has an ordered and even structure.

The theory section describes the austenitic stainless steel weld material as very coarse grained with columnar grains in the order of millimetres, the same size scale as the weld defects that must be detected. The structure that can be seen in the weld material in figure 4.1 matches the description of the grain structure in the theory section, but it has *not* been definitively confirmed that the structures seen are the individual grains.

The first three weld passes has a rather circular melt area and the columnar structures (possibly the grains) are oriented towards the centre of the circles, i.e. parallel with the thermal gradient, which was predicted for grain growth during solidification of the weld pool, according to the theory.

The remaining weld passes are rather wide and flat. The width of the weld passes increases for each new layer, but eventually the width of the gap becomes too big and the weld cannot cover it completely with the melt. Around weld pass number seven, when roughly half of the weld was completed, the next pass was placed on one side of the weld region, to the right in figure 4.1. This causes the structures to be tilted towards the top-left corner of the figure, thus the weld is no longer symmetrical around the weld axis.

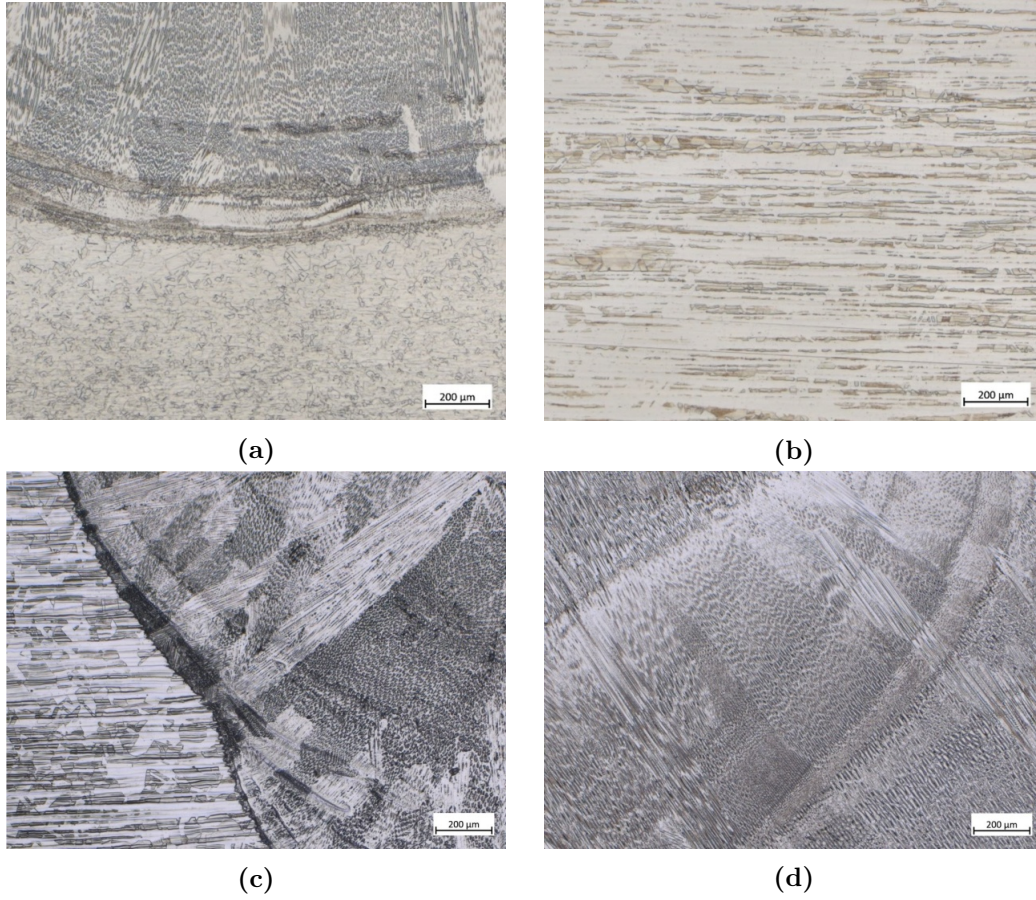
This anisotropic structure affects the behaviour of the ultrasonic beams that is used for weld quality inspection. Placing the ultrasonic probe on either side of the weld cap result in different sensitivity to defects in various positions because of the anisotropy. The beam path deviation, beam splitting and scattering as discussed in the theory section is going to be different when measuring from either sides and must be taken into account.



**Figure 4.1:** Metallographic cross-section of the 11 T dipole weld. The individual weld passes can be identified and a columnar structure, tilted towards the top-left corner of the image can be seen. More details in areas (a), (b), (c) and (d) are given in figure 4.2. Courtesy M. Meyer, CERN, EN-MME.

Figure 4.2(b) show the 316LN parent metal and shows horizontal lines in a structure that is very different from the weld metal. The backing plate shown in figure 4.2(a) show a homogeneous isotropic structure. The parent metal structures could be explained by the process when forming the backing plate and the original plates of the half shells [54]. Assuming that the structures observed in the images are in fact the grains, then grain coarsening is observed close to the weld fusion line with an almost quadrupling of the grain size. Still, the grain size is significantly smaller than in the weld metal which is best seen in figure 4.2(c)

Figure 4.2(c) and 4.2(d) show the fusion of weld material to the weld bevel and the centre weld metal respectively. Again, assuming that it is the individual grains that is seen, a sub-grain micro-structure is clearly observed inside the grains, and both columnar and equiaxed sub-grain structure can be identified. (This is also supported in the literature of 316LN austenitic stainless steel weld material [36] presented in the theory section, however must be confirmed by a different microscopy method.) Because of the inhomogeneities presented in sub-grain boundaries such as different chemical composition and lattice disorders, the ultrasonic waves suffer from higher attenuation and scattering compared to a weld material without sub-grain structure.

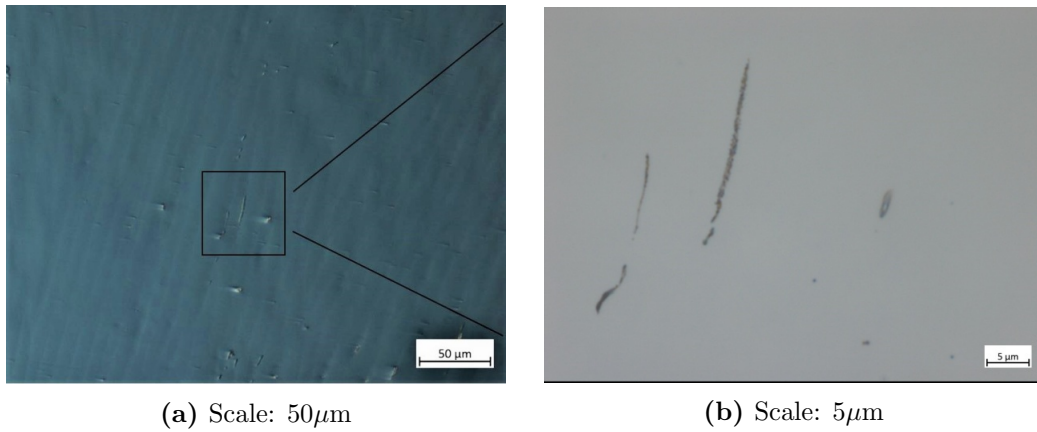


**Figure 4.2:** Metallographic images of the marked areas in figure 4.1. (a) Weld material fused to the backing-plate. (b) 316LN half shell parent material. (c) Weld material fused to the 316LN half shells. (d) Centre of the weld material. Courtesy M. Meyer, CERN, EN-MME

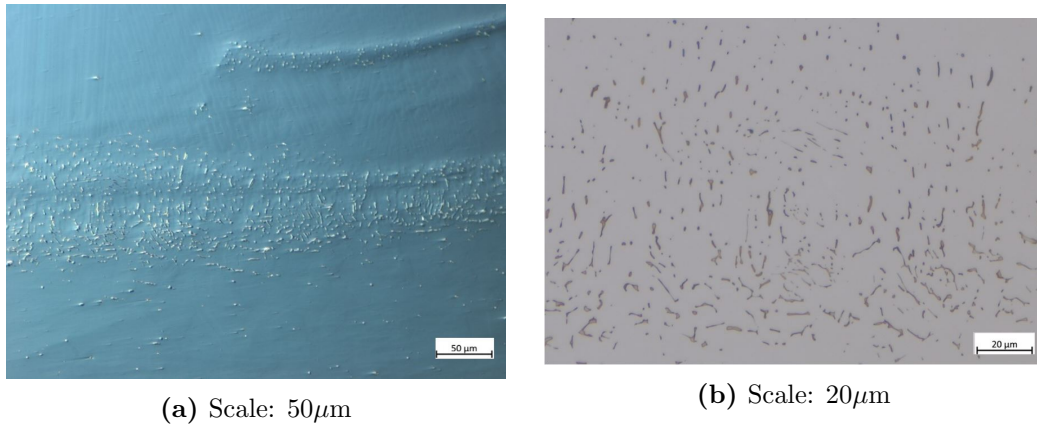
After polishing up to  $1\ \mu\text{m}$  the sample was submitted to Murakami etching to expose  $\delta$ -ferrite and inter-metallic  $\sigma$ -phase precipitates. Using Differential Interference Contrast microscopy (DIC), the general weld structure could be visualized. Figure 4.3(a) show a precipitate under DIC-light and a zoom-in image of the same precipitate but under normal light is shown in figure 4.3(b). Only very small amounts of precipitates were observed in the weld metal and no precipitates were found in the 316LN austenitic stainless steel half shell parent metal.

In the fusion line of the weld to the backing plate, significant amounts of precipitates were found as shown in figure 4.4. In addition, small amounts of ferrite was found in the backing plate material which is common for a 304 grade austenitic stainless steel, however very uncommon for 316LN grade. A chemical composition analysis can aid in determining the type of steel of the backing plate.

The very small amounts of precipitates in the weld material is not expected to affect the ultrasonic inspection. The relatively large amounts of precipitates where the weld material has fused to the backing plate is a bigger issue and may cause increased amounts of background signals from the root. However, the effect is expected to be very small due to the similar acoustic impedance of ferrite ( $Z = 46.7$  for mild steel) and austenite ( $Z = 44.8$  for stainless steel) [19]. Using equation 2.3 from the theory section gives a reflectivity of  $E_r = 0.04\%$ , so the ferrite/austenite interface is a very bad reflector and most likely go undetected.



**Figure 4.3:** (a) Metallographic image under DIC-light for visualizing the weld structure and to find the location of the precipitates. (b) Metallographic image under normal light where long and thin precipitates are visible. Courtesy M. Meyer, CERN, EN-MME.

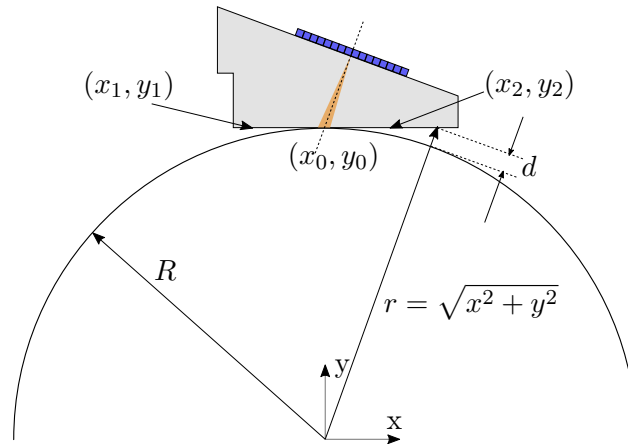


**Figure 4.4:** (a) Metallographic image of the junction between weld material and backing plate under DIC light to enhance the structure of the weld. A relatively large amount of precipitates is observed. Small amounts can be seen in the backing plate as well. (b) Metallographic image of the weld to backing plate junction under normal light showing the precipitates. Courtesy M. Meyer, CERN, EN-MME.

## 4.2 The Effect of the Stainless Steel Half Shells on Ultrasonic Beam Dynamics

### 4.2.1 Wedge-Surface Distance

For a good coupling of sound from the wedge and the test object, the gap between the wedge and test piece should not exceed  $d = 0.50$  mm according to ISO 17640 [13]. Because the wedge shoe is flat and the cylindrical 11 T dipole magnet surface is not, only a small part of the wedge in actual contact with the magnet surface and a gap is obtained, illustrated in figure 4.5. Water is used as a coupling medium between the wedge and the surface. The water is continuously pumped through the irrigation ports of the wedge which ensures that a film of water is obtained between the two surfaces throughout the scan.



**Figure 4.5:** An exaggerated illustration of the gap between wedge and surface due to curvature.

Assuming that the contact point  $(x_0, y_0) = (0.0, 0.0)$  of the wedge coincides with the beam exit point, i.e. the point where maximum wave energy leaves the wedge, one can calculate the wedge to surface distance for any point of the wedge using the equation 4.1.

$$d = r - R = \sqrt{x^2 + y^2} - R \quad (4.1)$$

The maximum width of the beam was calculated where point 1 and point 2 in figure 4.5 is the extreme ends where the beam exits the wedge. Point 1 was calculated to  $(x_1, y_1) = (-9.1, 285.0)$  mm, which gives  $d = 0.15$  mm. Point 2 was calculated to  $(x_2, y_2) = (8.5, 285.0)$  mm, which gives  $d = 0.13$  mm. The requirement that  $d < 0.50$  mm is fulfilled with good margin, and therefore the wedge can be used without any changes to its dimensions.

### 4.2.2 Beam Spread due to the Cylindrical Surface

The use of a flat wedge in the inspection of the cylindrical 11 T dipole horizontal welds will cause a significant beam spread which must be taken into account for the interpretation of the PAUT results, especially when determining the position of potential weld defects. Snells law states that the refraction and reflection angles depend on the incidence angle of the ultrasonic beam according to equation 2.5, as described in theory.

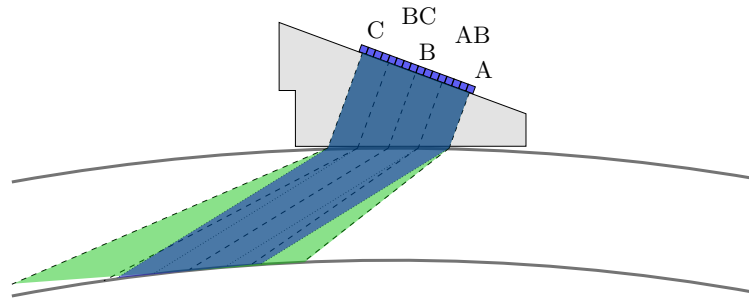
Figure 4.6 illustrate the refraction angles obtained for a beam without beam steering or focusing. The blue area shows the beam refraction if a flat surface was inspected. The green area shows the additional coverage when inspecting on the cylindrical surface of the 11 T dipole magnets.

Figure 4.7 show a graph of the beam spread that is obtained in the inspection of the 11 T dipole half shell welds if no focusing of the ultrasonic beam is used. Point A, AB, B, BC and C is indicated in figure 4.6.

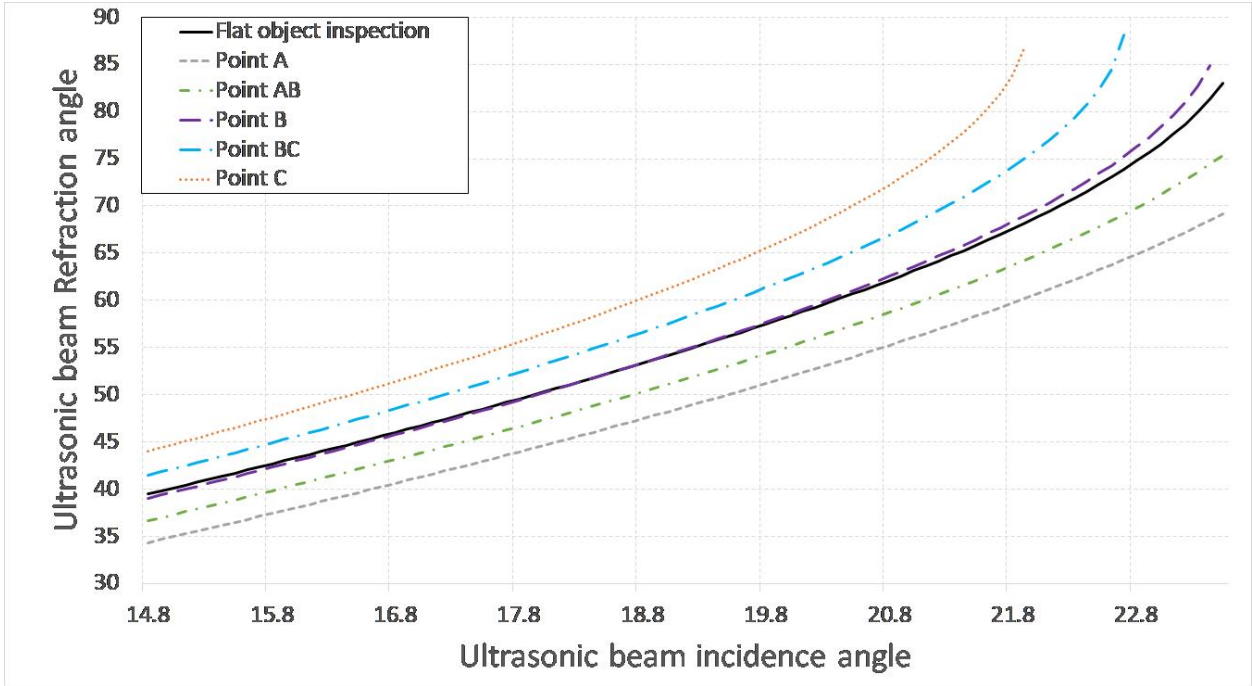
Most of the ultrasonic energy exits the wedge close to point B, which has about the same refraction angle as when inspecting an object with a flat surface. This means that defects are detected with the strongest signal amplitude at, or very close to, the correct angle.

The graph shows that the beam spread between point AB and BC is much less than between point A and C. When considering this centre part of the ultrasonic beam, the total beam spread is about  $+3^\circ$  and  $-2.5^\circ$  for a  $55^\circ$  beam. For beam steering above  $72.5^\circ$ , the total beam spread reaches its maximum, and parts of the ultrasonic beam is propagating at a  $90^\circ$  angle, i.e. parallel to the surface.

Beam spread has a negative impact on sizing of defects where they appear larger than normal and the noise level will increase due to dispersed energy from the desired area to the surroundings. For beam steering above  $72.5^\circ$  a large portion of the beam is expected to travel close to the surface which can be used for detection of surface and near surface defects, although with a weak signal amplitude. The depth localization and sizing of near surface defects in the PAUT set-up are not accurate where defects appear smaller than they actually are, and at a deeper position in the weld volume.



**Figure 4.6:** Ultrasonic beam spread due to the inspection of a curved surface. The blue area shows beam propagation in the case of a flat piece (dotted lines). The blue and green area combined is for curved surface (dashed lines).

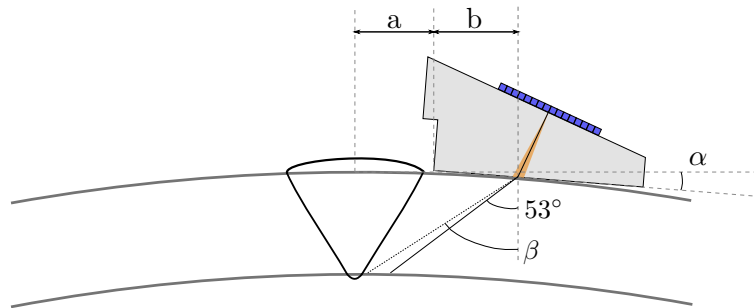


**Figure 4.7:** Graph showing the calculated beam spread of the refraction angles obtained in the 11 T dipole half shells versus incidence angles in the wedge. Beams above approximately  $70^\circ$  have a particularly large beam spread. The curves are calculated for the beams originating from point A, AB, B, BC, and C in figure 4.6. The solid line indicates the refraction angle for an inspection on a flat surface.

#### 4.2.3 Beam Angle Offset due to the Cylindrical Surface

The curvature of the surface of the 11 T dipole magnet, and the wedge displacement from the centre of the tube creates an angle offset,  $\alpha$ , shown in figure 4.8. This offset angle was calculated for the case that the probe is placed 2 mm apart from the weld cap ( $a + b = 22$  mm from weld centre) which gives  $\alpha = 4.4^\circ$ . For example, the  $53^\circ$  beam is offset by  $4.4^\circ$  to  $\beta = 53 + \alpha = 57.4^\circ$ .

This affects the accuracy of determining the position of the defects. Defects appear to reside shallower than their actual position.



**Figure 4.8:** Illustration of the angle offset,  $\alpha$ , due to the curvature of the 11 T dipole half shell.

### 4.3 Comparison of PAUT Focal Laws

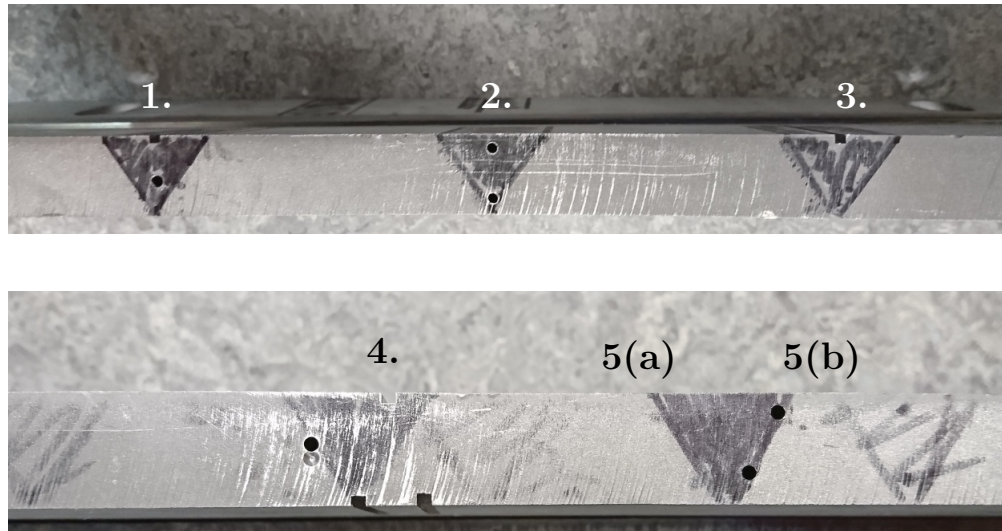
In order to compare different focal laws, and to determine a good focal law for the PAUT inspection of the 15 mm thick austenitic stainless steel welds of the 11 T dipole magnets, a flat 16 mm thick, austenitic stainless steel block was used, shown in figure 4.9.

$\varnothing = 2$  mm SDHs and 1.5 mm deep notches were machined in various positions in the block. Five areas have been marked with a permanent pen, and each area simulate a weld with defects. The probe was placed parallel to and close to the "weld" area which would be the case during a real weld inspection. Only the signals from identical artificial defects at different positions was compared, therefore the SDHs in "weld" areas 1, 2 and 5 were used.

Four different focal laws with focus at 15 mm, 20 mm, 25 mm and 30 mm sound path have been compared for sensitivity and for their accuracy of locating the artificial defects in depth below the surface, length away from the probe and the length of the sound path. No sensitivity calibration was done for these measurements since it would interfere with the focusing effects of the calculated focal laws. However, range calibration was necessary to get representative distance readings.

The two focal laws with focus at 25 mm and 30 mm sound path were found to have the best accuracy in determining the position of the defects. The different focal laws sensitivity to detect the SDHs was also compared. After considering the defocusing properties, i.e. beam spread, of the cylindrical surface of the half shells, a focus of 20 mm or 25 mm sound path was found to have the strongest sensitivity to the defects.

From these comparisons, a focal law with focus at 25 mm sound path was determined to have the best properties for the inspection of the 11 T dipole horizontal welds.



**Figure 4.9:** A 16 mm thick flat austenitic stainless steel block with SDHs and notches. The black pen markings show a "weld" area(1, 2, 3, 4 and 5) with artificial defects.

#### 4.3.1 The Effect of the Range of Beam Steering Angles

Ultrasonic inspections that uses longitudinal wave probes suffer from mode converted signals, i.e. a conversion from longitudinal waves into shear waves as described in the theory section. This effect is mostly observed for angled ultrasonic beam inspections. The amount of mode conversion increases with the incidence angle of the ultrasonic beam [20]. An angled beam inspection is used

for the 11 T dipole half shell welds, where the phased array probe is producing longitudinal waves, incident with an angle towards the half shell surface.

To avoid an excessive amount of mode converted signals which can cause confusion in the interpretation of the data, a maximum beam steering angle of  $80^\circ$  was chosen. Similarly, to avoid excessive number of signals from the beams that are reflected from the backside of the half shells, a minimum beam steering angle of  $40^\circ$  was chosen.

#### 4.3.2 The Effect of Focus Length on Distance Readings

To compare the differences in distance readings due to the focus length of the focal law, the probe was placed facing each of the "weld" areas, and readings from all four focal laws were taken without moving the probe. The depth, length and sound path distances were measured with a ruler and is shown in table 4.1. Based on these measurements, the required ultrasonic beam angle was calculated.

**Table 4.1:** Measured distances using a ruler for the reflectors of each "weld" area of the block in figure 4.9. The left side of area 5 is called 5(a) the right side is called 5(b).

| Reflector       | Angle ( $^\circ$ ) | Depth (mm) | Length (mm) | Sound Path (mm) |
|-----------------|--------------------|------------|-------------|-----------------|
| 1. SDH          | 67.8               | 8.5        | 10.5        | 22.5            |
| 2. Bottom SDH   | 60                 | 12         | 10          | 24              |
| 2. Top SDH      | 81.8               | 3          | 10          | 21              |
| 5(a) Top SDH    | 84.3               | 3          | 18.5        | 30              |
| 5(a) Bottom SDH | 66.9               | 11         | 14          | 28              |
| 5(b) Top SDH    | 76.1               | 3          | 1           | 12.5            |
| 5(b) Bottom SDH | 56.6               | 11         | 5.5         | 20              |

The distance readings from the PAUT inspection are given in table 4.2 for each of the focus lengths. The difference between the measured distance and the actual distance is presented in *italic*.

On average, the depth measurements for the four focal laws are a bit too shallow and the length measurements a bit too long. The sound path measurement is very accurate and deviate less than 1 mm for most echoes. The exception is when focus is placed very close to the probe at 15 mm sound path, and for the reflections at very large angles, above  $75^\circ$ .

The focal laws with focus at 25 mm and 30 mm has length, depth and sound path measurements which deviate less than 1 mm for most SDHs. The focal law with focus at 30 mm sound path show the most accurate distance measurements. The two other focal laws with focus at 15 mm and 20 mm sound path have deviations in length, depth and sound path larger than 1 mm for many SDHs. It was therefore decided that these two focal laws will not be used for weld inspection.

The special cases when the required ultrasonic beam angle is larger than  $80^\circ$  to reach the SDHs are interesting because these defects are still detectable although beam steering is limited between  $40^\circ$  to  $80^\circ$ . However, the amplitude of the signals from these defects are very low.

**Table 4.2:** Angle and distance readings for reflectors in the flat block. Measuring from the left and right side of area 5 is called 5(a) 5(b) respectively. Values in *italic* is the difference between measured and real values (=meas-real).

| Reflector       | Angle (°)                 |      | Depth (mm) |       | Length (mm) |      | Sound path (mm) |       |
|-----------------|---------------------------|------|------------|-------|-------------|------|-----------------|-------|
|                 | Focus at 15 mm sound path |      |            |       |             |      |                 |       |
| 1. SDH          | 73                        | 5.2  | 6.68       | -1.82 | 11.88       | 1.38 | 22.85           | 0.35  |
| 2. Bottom SDH   | 65                        | 5.0  | 10.33      | -1.67 | 11.92       | 1.92 | 24.45           | 0.45  |
| 2. Top SDH      | 80                        | -1.8 | 3.82       | 0.82  | 11.85       | 1.85 | 22.1            | 1.1   |
| 5(a) Top SDH    | -                         | -    | -          | -     | -           | -    | -               | -     |
| 5(a) Bottom SDH | 71                        | 4.1  | 8.96       | -2.04 | 15.99       | 1.99 | 27.52           | -0.48 |
| 5(b) Top SDH    | 77                        | 0.9  | 2.99       | -0.01 | 3.05        | 2.05 | 13.31           | 0.81  |
| 5(b) Bottom SDH | 60                        | 3.4  | 9.93       | -1.07 | 6.79        | 1.29 | 19.86           | -0.14 |
| Average         |                           | 2.8  |            | -0.97 |             | 1.75 |                 | 0.35  |
|                 | Focus at 20 mm sound path |      |            |       |             |      |                 |       |
| 1. SDH          | 70                        | 2.2  | 7.26       | -1.24 | 11.05       | 0.55 | 22.3            | -0.2  |
| 2. Bottom SDH   | 63                        | 3.0  | 10.89      | -1.11 | 11.07       | 1.07 | 23.98           | -0.02 |
| 2. Top SDH      | 80                        | -1.8 | 3.73       | 0.73  | 11.33       | 1.33 | 21.5            | 0.5   |
| 5(a) Top SDH    | 80                        | -4.3 | 5          | 2     | 19.27       | 0.77 | 29.55           | -0.45 |
| 5(a) Bottom SDH | 69                        | 2.1  | 9.67       | -1.33 | 15.09       | 1.09 | 26.97           | -1.03 |
| 5(b) Top SDH    | 76                        | -0.1 | 3.06       | 0.06  | 2.35        | 1.35 | 12.64           | 0.14  |
| 5(b) Bottom SDH | 58                        | 1.4  | 10.28      | -0.72 | 5.95        | 0.45 | 19.4            | -0.6  |
| Average         |                           | 0.36 |            | -0.23 |             | 0.94 |                 | -0.24 |
|                 | Focus at 25 mm sound path |      |            |       |             |      |                 |       |
| 1. SDH          | 69                        | 1.2  | 7.97       | -0.53 | 10.67       | 0.17 | 22.24           | -0.26 |
| 2. Bottom SDH   | 62                        | 2.0  | 11.18      | -0.82 | 10.67       | 0.67 | 23.81           | -0.19 |
| 2. Top SDH      | 80                        | -1.8 | 3.71       | 0.71  | 11.22       | 1.22 | 21.37           | 0.37  |
| 5(a) Top SDH    | 80                        | -4.3 | 5          | 2     | 18.76       | 0.26 | 29.03           | -0.97 |
| 5(a) Bottom SDH | 68                        | 1.1  | 10.05      | -0.95 | 14.75       | 0.75 | 26.82           | -1.18 |
| 5(b) Top SDH    | 75                        | -1.1 | 3.21       | 0.21  | 2.07        | 1.07 | 12.41           | -0.09 |
| 5(b) Bottom SDH | 57                        | 0.4  | 10.25      | -0.75 | 5.91        | 0.41 | 19.34           | -0.66 |
| Average         |                           | -.35 |            | -0.02 |             | 0.65 |                 | -0.43 |
|                 | Focus at 30 mm sound path |      |            |       |             |      |                 |       |
| 1. SDH          | 69                        | 1.2  | 7.87       | -0.63 | 10.4        | -0.1 | 21.95           | -0.55 |
| 2. Bottom SDH   | 61                        | 1.0  | 11.47      | -0.53 | 10.32       | 0.32 | 23.66           | -0.34 |
| 2. Top SDH      | 80                        | -1.8 | 3.69       | 0.69  | 11.07       | 1.07 | 21.23           | 0.23  |
| 5(a) Top SDH    | 80                        | -4.3 | 5          | 2     | 18.61       | 0.11 | 28.88           | -1.12 |
| 5(a) Bottom SDH | 67                        | 0.1  | 10.41      | -0.59 | 14.38       | 0.38 | 26.65           | -1.35 |
| 5(b) Top SDH    | 75                        | -1.1 | 3.17       | 0.17  | 1.93        | 0.93 | 12.27           | -0.23 |
| 5(b) Bottom SDH | 57                        | 0.4  | 10.52      | -0.48 | 5.64        | 0.14 | 19.31           | -0.69 |
| Average         |                           | -.64 |            | 0.09  |             | 0.41 |                 | -0.58 |

#### 4.3.3 The Effect of Focus Length on Detectability of Defects

The gain setting and the signal amplitude from the artificial defects were recorded at the same time as the distance readings in order to compare the detectability of defects for the four different focal laws. The results are presented in table 4.3 for five SDHs with different sound path distances.

The received signal amplitude increases with a smaller distance between the focus point and the defect, however the effect is not very strong. The low-lying SDH and the shallow lying SDH,

"5(b) Bottom SDH" and "5(a) Top SDH" respectively, had the same gain setting for the focal laws, and clearly show that using a focus distance which is close to the defect gives a stronger signal.

The sensitivity of the inspection is dependent on the angle of the ultrasonic beam where larger angles require more gain to raise the signal amplitude of the defects to approximately 80% which is also shown in table 4.3. This is the reason why the angular-corrected-gain (ACG) sensitivity calibration is required. The shallow defects which theoretically require an ultrasonic beam above  $80^\circ$  is detected in this PAUT set-up, however the gain required to raise their signal amplitudes are very large.

The sound path distances to the areas of interest are approximately between 20 and 30 mm. Therefore, after considering the defocusing properties (beam spread) of the cylindrical geometry in the inspection of the 11 T dipole magnets, a focus between 20 and 25 mm should be considered.

**Table 4.3:** Comparison of amplitude response of five defects shown in figure 4.9 for the four focal laws. The gain and amplitude is presented along with distance between focal point and defect for each focal law.

| Focus length(mm)                                                   | Distance, focus to defect (mm) | Gain (dB) | Amplitude (%) |
|--------------------------------------------------------------------|--------------------------------|-----------|---------------|
| <b>1. SDH, 22.5 mm sound path(<math>67.8^\circ</math>)</b>         |                                |           |               |
| 15                                                                 | -7.5                           | 34        | 80            |
| 20                                                                 | -2.5                           | 31        | 74            |
| 25                                                                 | 2.5                            | 31        | 73            |
| 30                                                                 | 7.5                            | 31        | 70            |
| <b>2. Bottom SDH, 24 mm sound path (<math>60^\circ</math>)</b>     |                                |           |               |
| 15                                                                 | -9                             | 34        | 85            |
| 20                                                                 | -4                             | 31        | 82            |
| 25                                                                 | 1                              | 31        | 87            |
| 30                                                                 | 6                              | 31        | 83            |
| <b>5(b) Bottom SDH, 20 mm sound path (<math>56.6^\circ</math>)</b> |                                |           |               |
| 15                                                                 | -5                             | 27        | 70            |
| 20                                                                 | 0                              | 27        | 86            |
| 25                                                                 | 5                              | 27        | 83            |
| 30                                                                 | 10                             | 27        | 77            |
| <b>5(b) Top SDH, 12,5 mm sound path (<math>76.1^\circ</math>)</b>  |                                |           |               |
| 15                                                                 | 2.5                            | 33        | 83            |
| 20                                                                 | 7.5                            | 33        | 72            |
| 25                                                                 | 12.5                           | 33        | 57            |
| 30                                                                 | 17.5                           | 33        | 51            |
| <b>5(a) Top SDH, 30 mm sound path (<math>84.3^\circ</math>)</b>    |                                |           |               |
| 15                                                                 | -15                            | -         | -             |
| 20                                                                 | -10                            | 48        | 52            |
| 25                                                                 | -5                             | 46        | 54            |
| 30                                                                 | 0                              | 46        | 58            |

## 4.4 Discussion of the Results of Ultrasonic Beam Dynamics and Comparison of PAUT Focal Laws

The microscopy of the 11 T dipole weld cross-section revealed an asymmetric weld structure where the sonic properties, according to the theory (chapter 2), is different when inspecting from either side of the weld.

The geometry of the horizontal welds of the 11 T half shells affects the ultrasonic beam dynamics and must be taken into account in the interpretation of the results. Weld imperfections will appear larger than normal due to the beam spread caused by the cylindrical surface. In addition, shallow defects, reached by ultrasonic beams larger than  $70^{\circ}$ - $75^{\circ}$  will appear as surface breaking defects independently if they are or not (figure 4.7).

Furthermore, the cylindrical geometry of the half shell welds causes an offset of  $+4.4^{\circ}$  of the ultrasonic beam as shown in figure 4.8, causing defects to appear more shallow than the actual case. However, unlike the calculations, the real half shell weld area is not a perfect cylinder and dissimilarities in the geometry is difficult to predict, so the offset can differ slightly. Though the effect is quite small as shown in chapter 5.

Several different PAUT focal laws have been calculated. Through the comparison of distance readings and signal amplitude for different focus lengths, a focal law with focus at 25 mm sound path has been selected for the routine inspection of the 15 mm thick austenitic stainless steel 11 T dipole welds. The defocusing properties (beam spread) due to the cylindrical geometry of the half shells and the sound path distance to the area of interest were taken into account.

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# 5

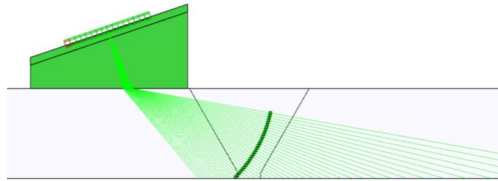
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## PAUT OF THE 11 T DIPOLE MAGNET WELDS

### 5.1 Results of Calibration and Reference Weld Samples

The calibration and reference blocks of the 15 mm thick 11 T dipole half shell austenitic stainless steel welds shown in section 3.4, was inspected with the PAUT set-up. The focal law parameters for the PAUT set-up are shown in the list below. It was calibrated for sensitivity on the  $\varnothing = 2$  mm side-drilled-holes (SDH) in the centreline of one of the weld samples. The probe was placed to scan parallel to the weld at a distance of 2 mm from the weld cap edge unless stated otherwise. Different types of artificial defects in various positions in the weld samples have proven to be detected in only one or two scans using the specially developed scanner.

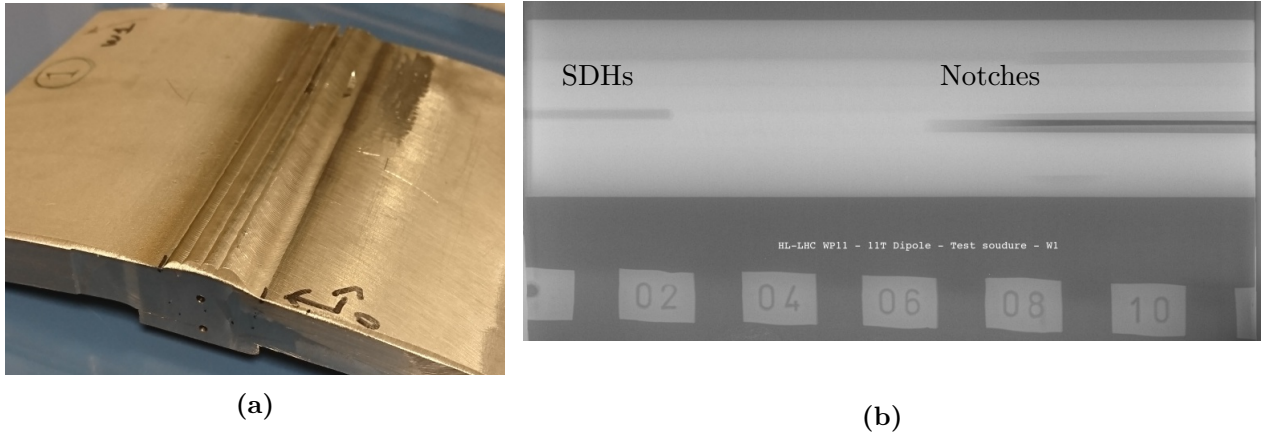
- Wave mode: Longitudinal compression
- Scan mode: Sectorial
- Initial angle:  $40^\circ$
- Final angle:  $80^\circ$
- Step size:  $1^\circ$
- Index offset: -11 mm
- Skew angle:  $90^\circ$
- Focus type: Half path
- Focus depth: 25 mm



**Figure 5.1:** Focal law simulation of the PAUT set-up for inspection of the calibration and reference samples

#### 5.1.1 Sample With Side-Drilled-Holes in the Weld Centreline and Surface Notches

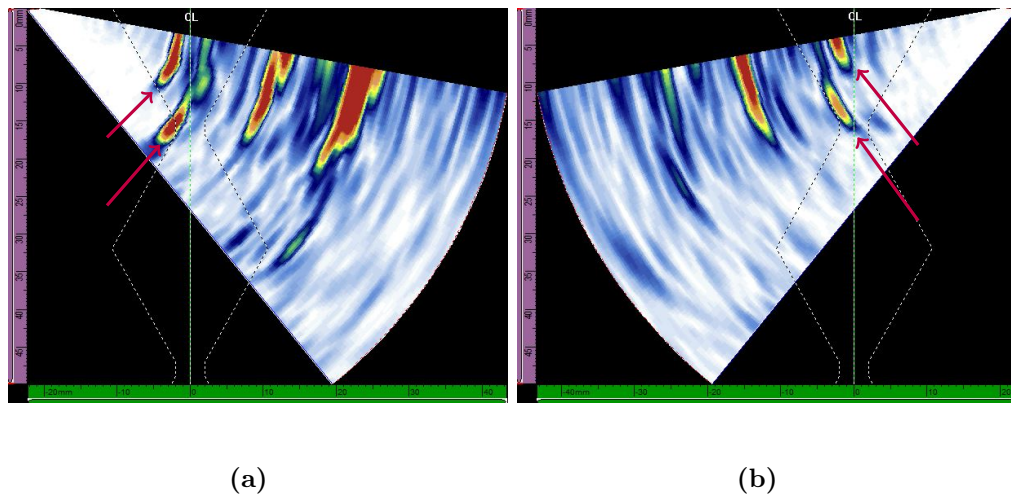
One weld sample, shown in figure 5.2(a), has two areas with artificial defects. In each end of the block SDHs in the weld centreline and notches were machined as shown in figure 3.11 in section 3.4. Figure 5.2(b) shows a radiography of the block with the SDHs to the left and notches to the right. No natural defects were found.



**Figure 5.2:** (a) Image of the centreline SDH weld sample where two SDHs can be seen in the front of the block and two top surface notches can be seen in back. (b) Top view radiographic image of the centreline SDH weld sample where the SDHs are seen as one dark line because they overlap. The bottom and top centre notches overlap slightly while the side notches are clearly distinguished. No natural defects were found.

The weld sample was inspected from both sides of the weld with the probes parallel to the weld at a 2 mm distance from the weld cap. Two significantly different responses from the centreline SDHs were received. For the left-side inspection (figure 5.3(a)) the amplitudes were 140% and 151% FSH for respective hole. In the right-side inspection (figure 5.3(b)), the amplitudes were 85% and 81% FSH for the top and bottom SDH respectively. The sensitivity ACG calibration of the PAUT-setup was performed on these SDHs from the right side (figure 5.3(b)) which therefore should show 80% full-screen-height (FSH). However, the probe position was not exactly the same for the inspection as for calibration so small differences were observed.

In the inspection from the left side, the probe could be placed closer to the SDHs due to the constraints of the weld cap, and therefore a shorter sound path to the hole of approximately 2 mm was obtained. This and the anisotropy of the weld material, where ultrasonic beams of different directions are not equally attenuated as discussed in the theory chapter, could explain why the amplitude response is so much larger for this side. As expected, these defects would be judged unacceptable according to sensitivity level 2 from ISO 11666, particularly when viewed from the left side of the weld.



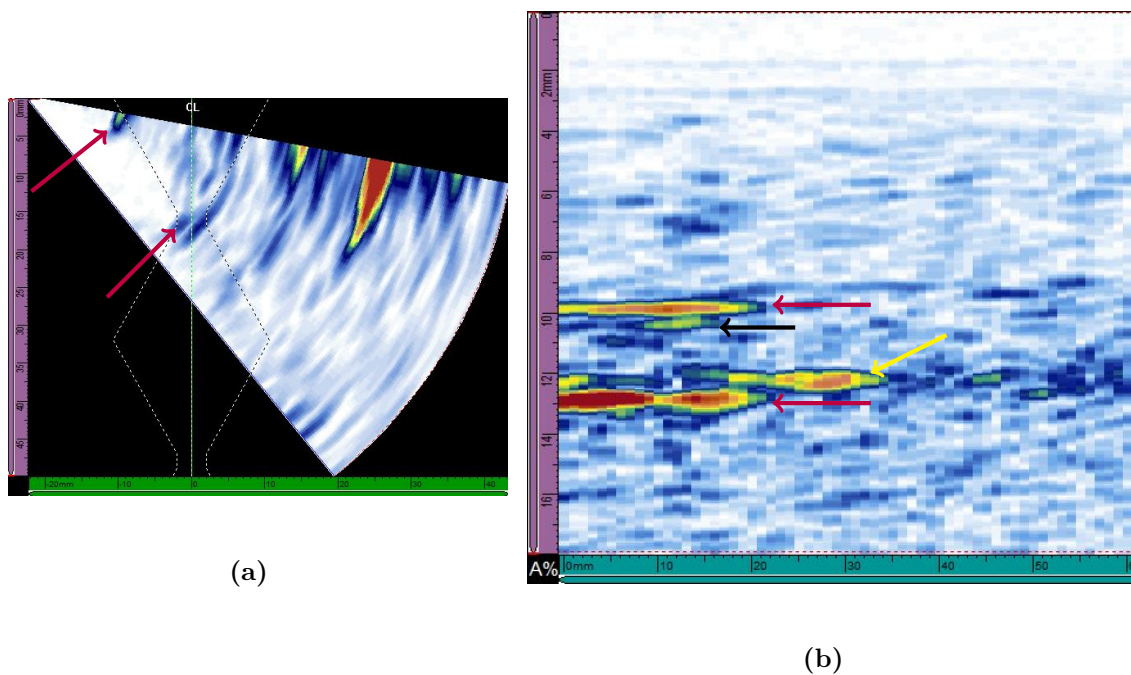
**Figure 5.3:** Left (a) and right (b) side S-scan respectively for the SDH area. The direct signals are marked with arrows. The other signals are combinations of skipped and mode-converted beams.

The detection of the 1 mm deep notches (counted from the half shell surface) are a bit more difficult to distinguish. The notch in the weld bevel is clearly detected with the direct reflection, shown in figure 5.4(a). The root notch has only a very weak direct signal and the centreline notch does not have one at all. Therefore it is necessary to look for the secondary signals in the skipped beam and mode converted zone, shown in figure 5.4(b).

The mode converted root signal at  $75^\circ$  increase in signal amplitude significantly to 88% FSH from background (30%-50%) when inspecting the root notch. The 55 mm long root notch signal can be distinguished from the 45 mm long centreline notch signals since these appear shorter in the scan by approximately 12 mm, consistent with the actual length of the notches. Two secondary signals from the 45 mm long notch have large amplitudes of 78% and 104%. A short signal of 65% amplitude, approximately 7 mm long, appear at the position of a 10 mm long shallow notch in the surface of the block.

Although it is possible to *detect* the notches through the mode converted and skipped secondary signals, it is required to have a direct signal to determine whether they are conforming or not. This can be obtained if the weld cap is removed.

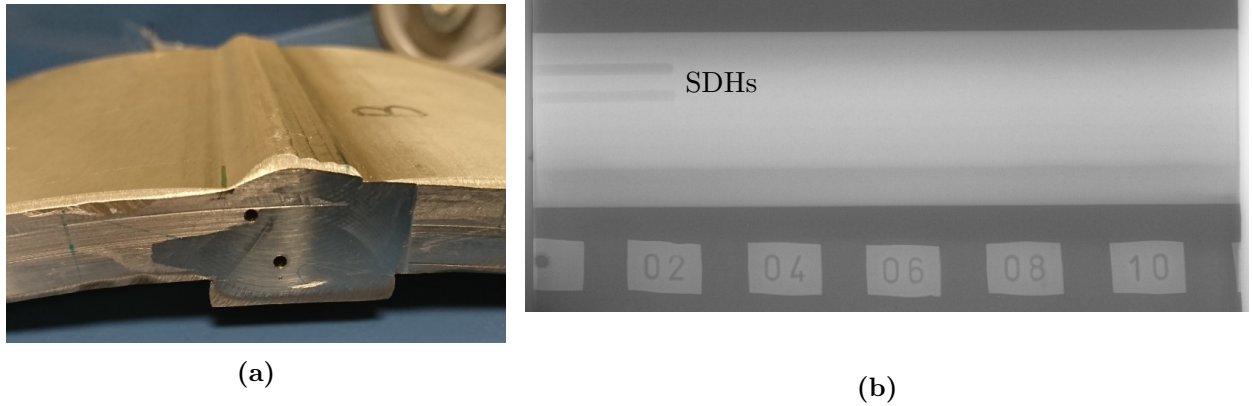
The root notch did not cause a strong direct signal because it was not machined in the correct position due to a design error. A root notch is typically a very strong reflector, however in this sample it was machined inside the junction between the weld and the backing plate. The normal case is to machine the root notch on the side of this junction.



**Figure 5.4:** (a) S-scan from the left side of the weld with notches. Arrows marks the direct signals from the surface notch in the weld fusion line and the root notch. (b) A 60 mm long  $75^\circ$  B-scan showing the skipped/mode converted signals of the notches. The black arrows mark the signals from the surface centreline notch, the yellow arrow mark the longer root notch signal and the red arrow mark the signal from a small surface notch.

### 5.1.2 Sample With Side-Drilled-Holes in the Fusion-Line

This sample is shown in figure 5.5(a) with two SDHs in the fusion line between the parent and weld material. A radiographic image of the block is shown in figure 5.5(b). No natural defects were found.

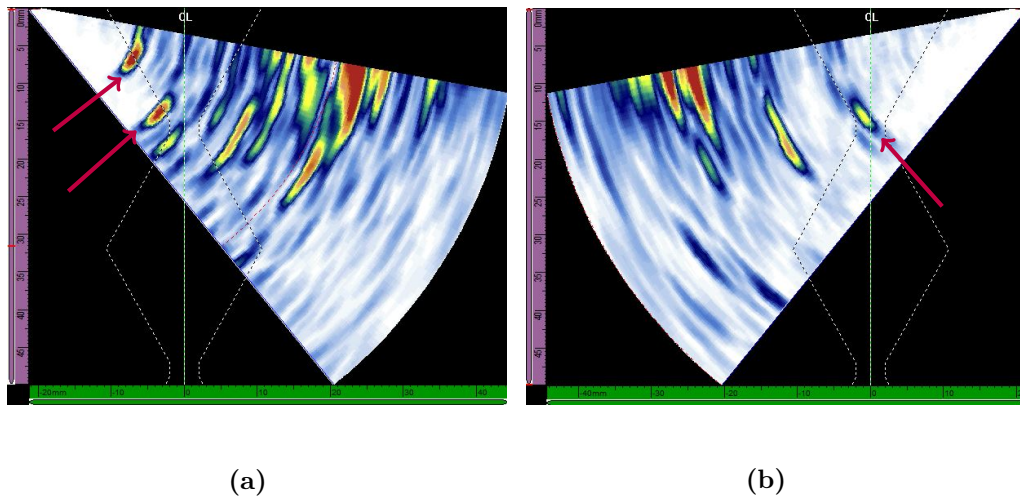


**Figure 5.5:** (a) Image of the fusion line SDH weld sample and b) Top view radiographic image of the same sample showing the two SDHs as dark lines. No natural defects were found.

Figure 5.6 show two S-scans of the weld sample with SDHs in the fusion line, which clearly show the importance of scanning on both sides of the weld. The direct signal amplitudes of the left scan (figure 5.6(a)) are 125% and 114% for the top and bottom SDH, respectively. For the right scan (figure 5.6(b)) only the bottom SDH had a direct signal of 60% and the top SDH is not detected.

The ACG calibration worked as expected where the amplitude changes due to beam angle difference has been compensated for, i.e. two same sized defects show the same response. The smaller amplitude of the bottom SDH can be explained by the longer sound path.

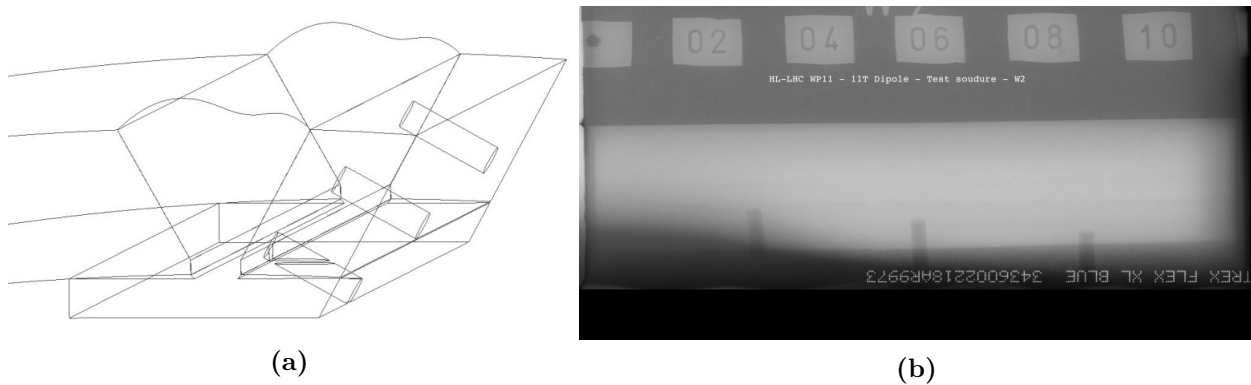
These two artificial defects would be judged as non-conform according to sensitivity level 2 from ISO 11666 because of their large amplitude signals from the left side.



**Figure 5.6:** Two S-scans of the SDHs in the fusion line when inspecting from the left (a) and right (b) side respectively. In (a) two direct signals appear at the correct position on the fusion line. In the right S-scan only the bottom SDH is detected with weak signal at the fusion line.

### 5.1.3 Sample With Flat-Bottomed-Holes in the Weld Bevel for Direct Detection

This sample with flat-bottomed-holes (FBHs) was designed for reference and evaluation of direct detection of flat defects such as Lack-of-fusion (LOF) at different heights in the weld bevel. A CAD model of the direct FBH block is shown in figure 5.7(a) and a radiography of the same sample is shown in figure 5.7(b).



**Figure 5.7:** The "direct FBH" block. (a) CAD model of the block where the position of the FBHs are seen. The low, middle and top lying FBHs are drilled to 13 mm, 9 mm and 4.5 mm below the top surface respectively. The radiographic image in (b) showed no natural defects.

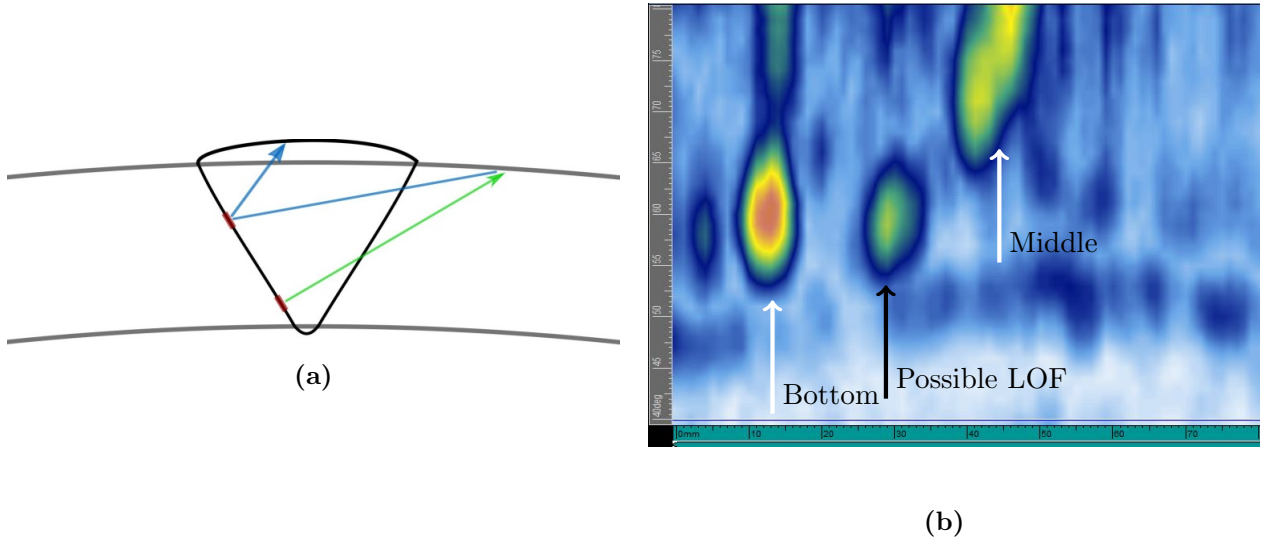
The C-scan in figure 5.8(b) show a C-scan acquired with the PAUT set-up where the low lying and middle FBH at 13 mm and 9 mm below top surface respectively, are detected with direct signals at 76% and 54% compared to a 20% noise level. The FBH machined at the highest position in the block was not detected.

The illustration in figure 5.8(a) show beam dynamics of the detection of LOFs in two different positions. The green arrow shows an ultrasonic beam that is incident perpendicular to the LOF and a direct reflection can reach the probe. The blue arrow shows a beam that is reflected upwards towards the weld cap for a LOF positioned high up in the weld.

The middle FBH, 9 mm below surface, has a rather weak signal although distinguishable, and marks the maximum height for a good direct detection of LOF. If it was possible to move the probe closer to the centreline of the weld it would be possible to detect LOF at higher positions which is the case if the weld cap is removed.

As seen in figure 5.8(b), a third signal is detected where no reflections should occur. It shows up exactly at the same depth as the lowest FBH and thus indicate that it is a natural defect, presumably a LOF, in the weld bevel close to the root. The amplitude is lower than for the 3 mm FBH. However, there is no sign of a defect at this position in the radiography of the weld, but since the defect is expected to be small it is possible that it was missed in the radiographic examination.

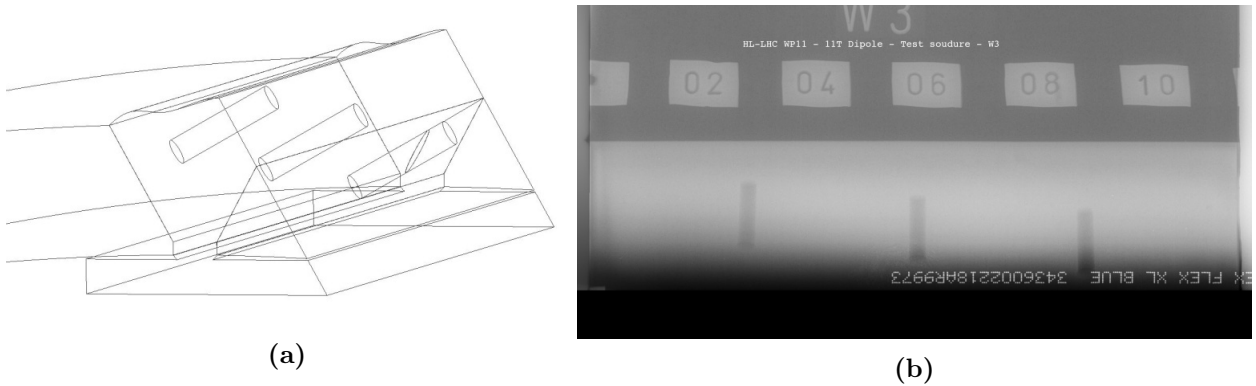
According to the acceptance level 2 in ISO 11666, only the low lying FBH, 13 mm from top surface, would be unacceptable. However, ISO 5817 states that flat defects such as LOF and cracks are not acceptable, which means that both the low and middle FBHs and the natural defect would be unacceptable if they are characterized to be flat defects.



**Figure 5.8:** (a) Illustration of the beam dynamics when inspecting the direct FBH block. (b) An 80 mm long C-scan where the bottom and middle FBH is detected and a possible natural defect, presumably a LOF.

#### 5.1.4 Sample With Flat-Bottom-Holes in the Weld Bevel for Indirect Detection

Similar to the "direct FBH", this sample was designed for reference and evaluation of flat defects, e.g. LOF or cracks, in the weld bevel but instead using skipped or mode converted beams, i.e. secondary signals. A CAD model of the indirect FBH block is shown in figure 5.9(a) and a radiographic image of the block is shown in figure 5.9(b), which didn't reveal any natural defects.



**Figure 5.9:** The "indirect FBH" block. (a) CAD model of the block where the position of the FBHs are seen. The low, middle and top lying FBH are drilled to 13 mm, 9 mm and 4.5 mm below the top surface respectively. The radiographic image in (b) showed no natural defects.

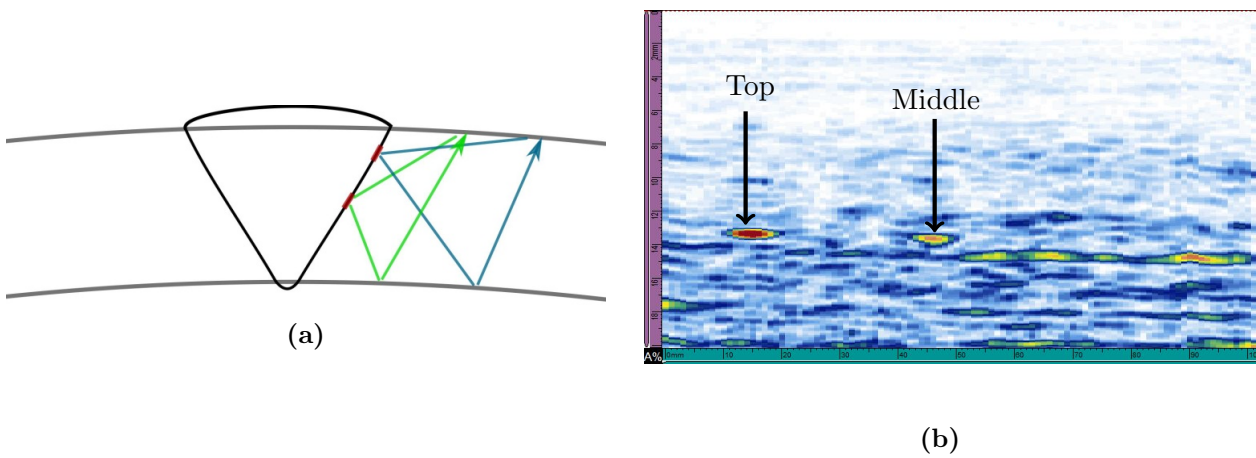
The three FBHs was machined to the same height (4.5 mm, 9 mm and 13 mm below top surface) in the weld bevel as for the other sample with FBHs. Figure 5.10(a) illustrate the beam dynamics for indirect detection of flat defects in the weld bevel, when the probes are placed parallel to the weld in two distances at 2 mm and 12 mm from the weld cap.

Figure 5.10(b) show a 72° B-scan of an inspection with the probe placed 6 mm from the weld cap where both the top and the middle FBHs, at 4.5 mm and 9 mm below top surface, was detected with rather strong signals of 154% and 72% amplitude respectively at noise <35%.

When the probe was placed close to the weld at 2 mm distance from the weld cap, the middle FBH was detected with a very strong signal of 139% amplitude. Noise was <40%. The top FBH

was barely detected in this probe configuration. Moving the probe further away from the weld to 12 mm from the weld cap, a large signal for the top lying FBH at 201% was obtained, compared to noise level <40%. The FBH machined 13 mm below surface, was not detected in any probe configuration.

The acceptability of these artificial defects cannot be concluded from the acceptance levels in ISO 11666 because they were only identified with secondary signals and not direct detection. Therefore, the weld cap must be removed so the probe can be placed directly on top of the weld and a direct signal can be obtained.

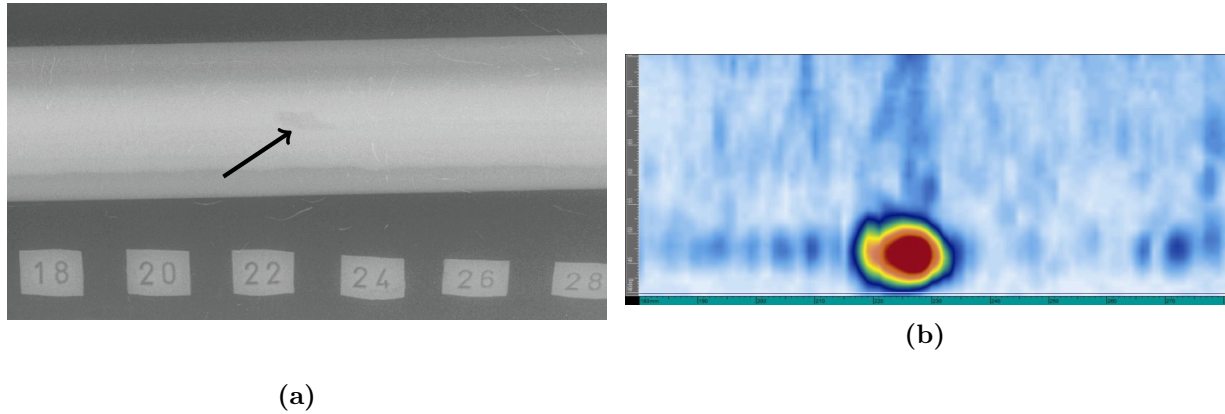


**Figure 5.10:** (a) Illustration of the beam when inspecting the indirect FBH block. The green arrow show probe position at 2 mm from weld cap and the blue arrow for probe position at 12 mm from weld cap. (b) A 100 mm long B-scan at 72° for a probe position at 6 mm from weld cap where both top and middle FBHs are detected.

### 5.1.5 Sample with Natural Defect

A natural defect was found in the radiography of a 35 cm long block of the same weld material as the reference and calibration blocks, i.e. the 15 mm thick austenitic stainless steel welds of an 11 T dipole prototype magnet. The defect was identified as a shrinkage cavity approximately 7 mm long and 3 mm wide, shown in figure 5.11(a)

The defect was clearly detected from probes on either side of the weld including when scanning the heat-affected-zone which indicate that the defect is volumetric and not flat as shown in figure 5.11(b). The signal amplitude was 153% and noise level <25%, which according to ISO 11666 is unacceptable.



**Figure 5.11:** (a) Radiography and (b) PAUT C-scan of a block with a natural shrinkage groove, approximately 7 mm long and 3 mm wide.

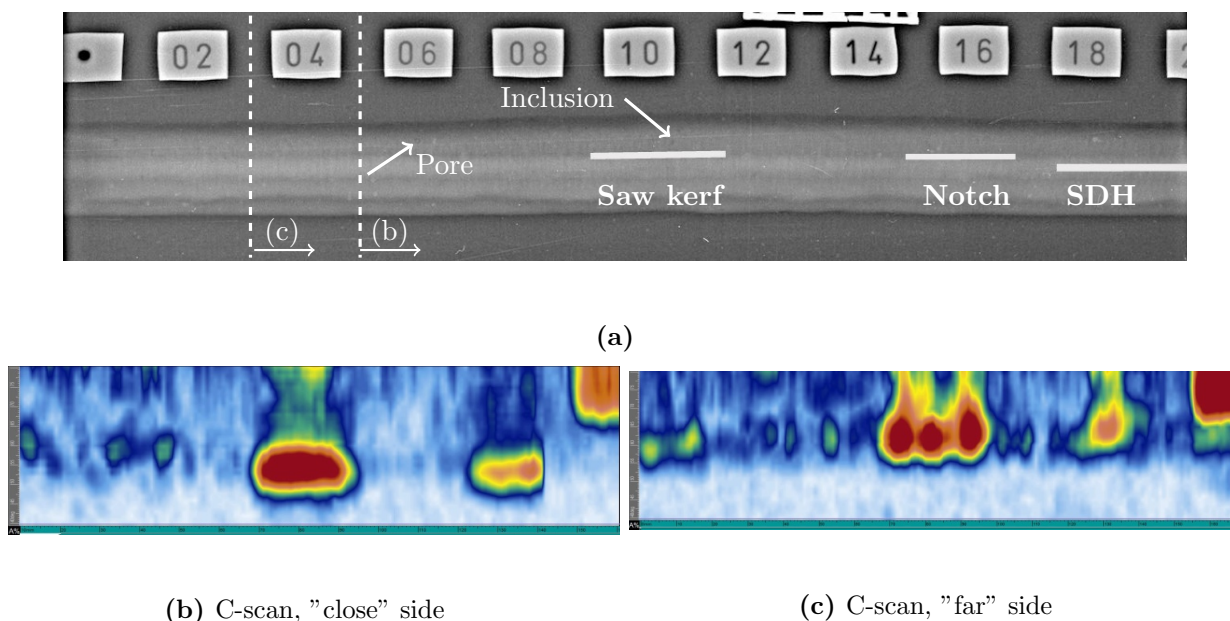
### 5.1.6 Two Weld Samples from 10 mm Thick LHC Main Dipole Half Shells

Two cylindrical austenitic stainless steel weld samples from an LHC main dipole magnet, 10 mm thick, were tested using the PAUT set-up. They were welded using MIG without backing plate.

A 20 cm long sample weld was inspected with radiography at high energy before artificial defects were machined into it, which revealed a 1 mm diameter porosity and a 0.5 mm diameter inclusion located close to the weld bevel, shown in figure 5.12(a). Three artificial defects were machined and are indicated in the radiography image. One 25 mm long, 2 mm deep saw kerf and a 20 mm long, 1 mm deep notch were machined right next to the root. A 30 mm long,  $\varnothing = 2$  mm SDH were machined in the centre of the weld. Two C-scans are shown in figure 5.12(b) and figure 5.12(c) for scanning on the "close" and "far" side respectively. The probe position where the ultrasonic beam can reach the root defects without propagating through the weld material is called "close-side", the other is called the "far-side".

All three artificial defects were detected with strong signals for both scans, however with slightly different result and with noise level  $< 30\%$ . The saw kerf had a signal amplitude of 140%, and the notch had 77% signal amplitude for both sides. The signal strength for the SDH differed significantly where the "close" side had 87% and "far" side had 148%.

The sonic anisotropy of the weld material is observed in the changes of the amplitude for the saw kerf which appear as three distinct points when the beam must travel through the weld material in the "far-side" scan. Also, the SDH has significantly different signal amplitude when measuring from either side of the weld even though the sound path is the same.

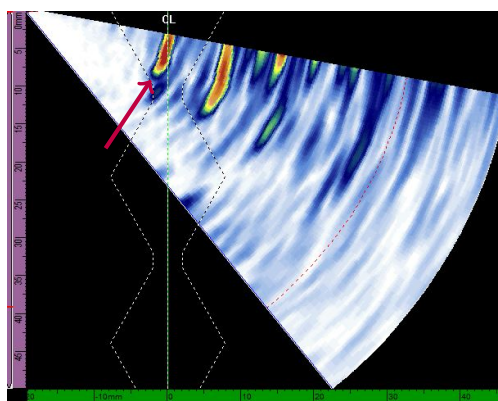


**Figure 5.12:** (a) Radiography of the 10 mm thick block with markings for a 1 mm diameter pore and a 0.5 mm diameter inclusion. A root saw kerf, a root notch and a SDH in the centre of the weld is marked which was machined after the weld was examined. (b) and (c) show a 150 mm long and a 170 mm long C-scan (marked in (a)) from inspection of the "close-side" and "far-side" respectively.

A second weld sample, 7 cm long, of the same type, i.e. 10 mm thick weld samples from the LHC main dipole, was also inspected with the PAUT set-up. This weld had two  $\varnothing = 0.9$  mm natural pores, revealed by a radiography, and two artificial defects. One  $\varnothing = 1$  mm and one  $\varnothing = 2$  mm SDH machined in the centre of the weld on either side of the sample.

The pores were not detected. The SDHs however were both detected with strong signal. Especially interesting is the 1 mm SDH which showed 114% amplitude (figure 5.13) which according to the standard ISO 11666 would be non-conform.

The acceptability of the defects in the two 10 mm thick weld samples cannot be determined because the sensitivity settings are not adjusted for a weld of this thickness. However, the fact that the  $\varnothing = 1$  mm SDH in the second weld was detected with a strong signal is a promising sign of the detectability of the PAUT set-up.



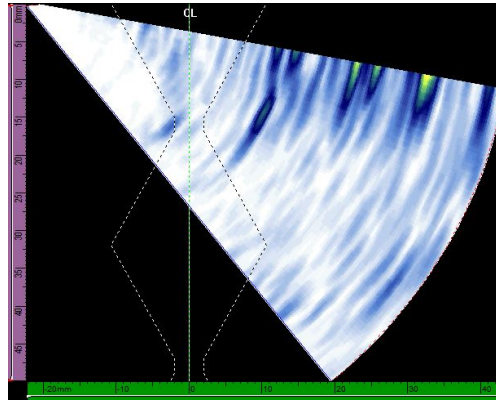
**Figure 5.13:** An S-scan of the  $\varnothing = 1$  mm diameter SDH showing an amplitude of 114%

### 5.1.7 Background Signals and Noise of the 11 T Dipole Welds

Figure 5.14 show typical background signals and noise from the 11 T dipole half shell weld inspection using the PAUT set-up with probes parallel to the weld and at 2 mm distance from the weld cap. The strong attenuation and scattering of the weld material is seen as increased noise as the ultrasonic beam enters the weld. Background signal(s) from the root are obtained as weak echoes originating from the fusion interface between the backing plate and the half shells.

The ultrasonic beams above approximately  $75^\circ$  have a large percentage of mode conversion into shear waves which will propagate with a different refraction angle and with approximately half of the speed of longitudinal waves. This, in combination with a large gain for the high angles obtained from the sensitivity calibration, gives rather strong background signals of approximately 50%. They originate from the different weld features, e.g. the shape of the weld cap or the weld to backing plate fusion. The inspections on either side of the weld do not show the same background signals or noise.

The PAUT signals from actual defects can be distinguished from the background since the background is always present and does not change much throughout the length of the inspection.

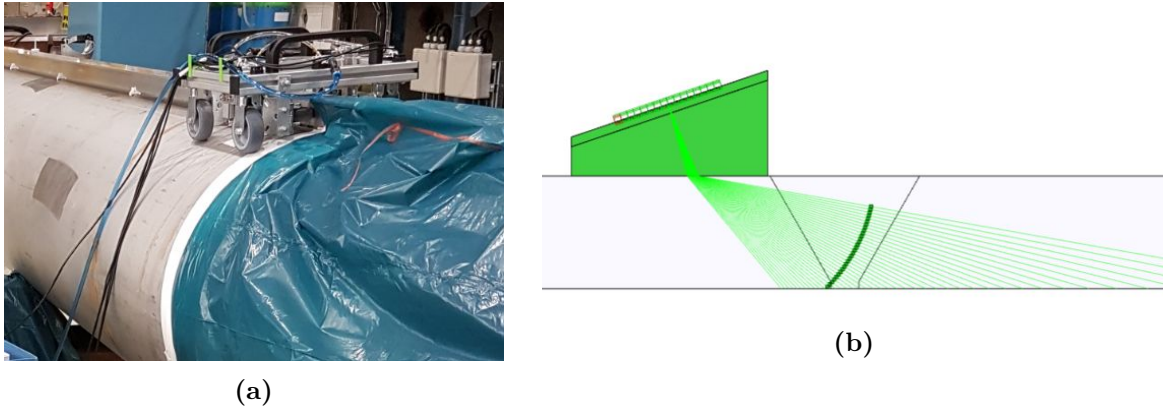


**Figure 5.14:** Typical background signals and noise for the PAUT set-up when inspecting the 11 T dipole welds.

## 5.2 Results of the 11 T Dipole Prototype Magnet Horizontal Welds

Because of lack of time, only one of the 5.5 m long horizontal welds of the 11 T dipole prototype magnet were inspected through the full length with the PAUT set-up, shown in figure 5.15(a). This weld is referred to as *weld A*. The probes were aligned parallel to the weld with a 2 mm distance to the weld cap. The set-up was calibrated for sensitivity on the  $\varnothing = 2$  mm SDHs in the "centreline SDH" weld sample.

The other weld, referred to as *weld B*, on the other side of the magnet was inspected at selected parts where a radiographic examination revealed defects, presumably lack-of-fusion. The scanner was used for this inspection, though it was manually aligned to the weld, i.e. the T-bar was not mounted. It was possible to keep a constant probe to weld distance in this scan because of the small scanning length of the selected areas. Based on the distance and focus measurements as described in section 4.3 a focal law with 25 mm sound path focus (figure 5.15(b)) was used.



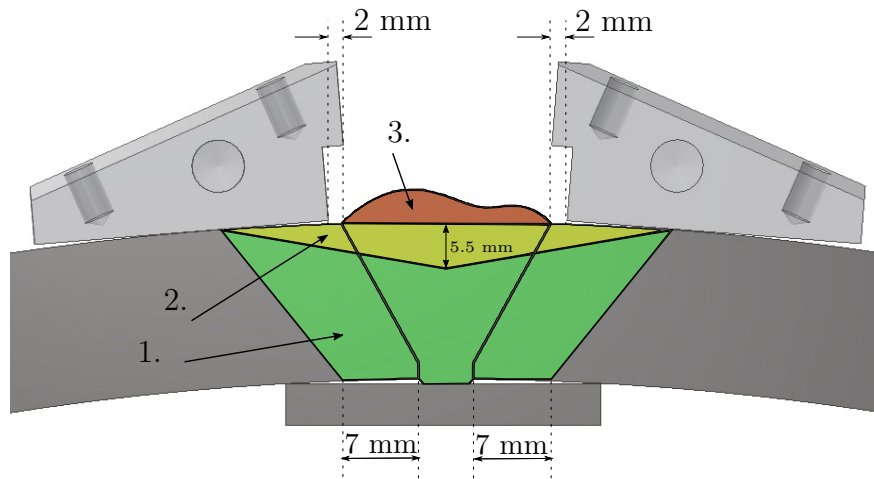
**Figure 5.15:** (a) Set-up for PAUT inspection of weld A. The T-bar and scanner is mounted on top of the weld. The magnet ends have been covered for protection from water spill during the inspection. (b) A simulation of the focal law with a focus at 25 mm for the PAUT

- Wave mode: Longitudinal
- Scan mode: Sectorial
- Initial angle:  $40^\circ$
- Final angle:  $80^\circ$
- Step size:  $1^\circ$
- Index offset: (-11 mm)
- Skew angle:  $90^\circ$
- Focus type: Half path
- Focus depth: 25 mm

Figure 5.16 illustrate how the probes are placed 2 mm from the weld cap and aligned with the weld. It also shows the coverage of the weld volume of the ultrasonic beam. Three zones of the 11 T dipole weld volume have been identified with different sensitivities for detecting defects. This is based on the calculations in section 4.2 which describe the effects of the cylindrical half shell surface on the beam dynamics. Also, ultrasonic beams with a large beam steering angle, approximately above  $75^\circ$ , are more attenuated and must pass through a larger amount of highly attenuating weld material to reach the centre of the weld.

The green zone (1.) is the angular range between  $40^\circ$  and  $75^\circ$  where beam spread and attenuation is low resulting in a good detectability. The yellow zone (2.) is the angular range above  $75^\circ$  where ultrasonic beam spread and attenuation is relatively large which causes a worse detectability. The red zone (3.) is the volume inside the weld cap which cannot be reached with a direct beam, only by skipped beams.

A minimum of approximately 7 mm of the heat-affected-zone on each side of the weld is covered when the probes are placed 2 mm from the weld cap.

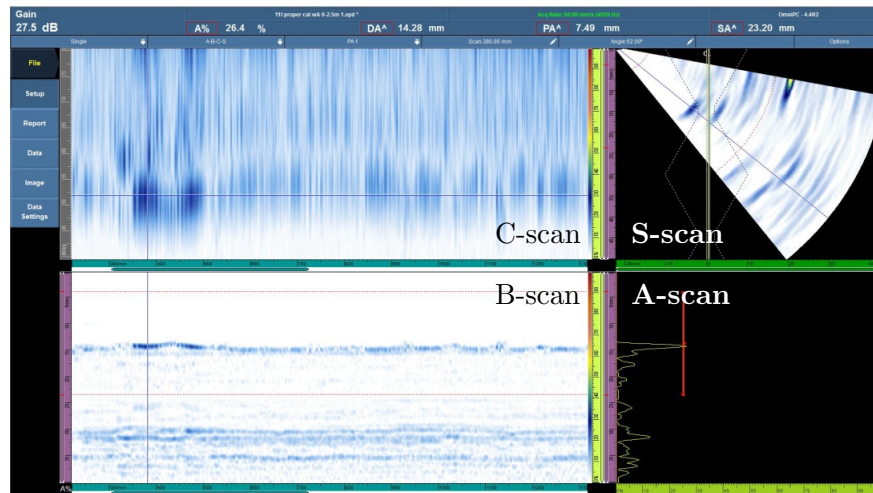


**Figure 5.16:** Cross-section illustration of the coverage of the weld volume for the 11 T dipole welds when the probes are placed 2 mm from the weld cap. Three zones with different sensitivity for defects are obtained.

### 5.2.1 Overview of Full Length Inspection of Weld A

Figure 5.17 show the C-, S-, B-, and A-scans of a 1 m long segment of weld A where the probe is placed with probe face 2 mm from the weld cap. The largest echo obtained in weld A is smaller than 30% FSH. For comparison, a  $\varnothing = 2$  mm SDH in the weld centre results in a signal of 80% FSH, and the noise level is about 20%.

According to the standard ISO 11666 weld imperfections causing an echo smaller than 63% FSH are acceptable provided that in scanning direction they are smaller than 15 mm. Thus, it can be concluded that weld A of the 11 T dipole prototype is conform and fulfils the requirements of weld quality level B according to ISO 5817 [11].

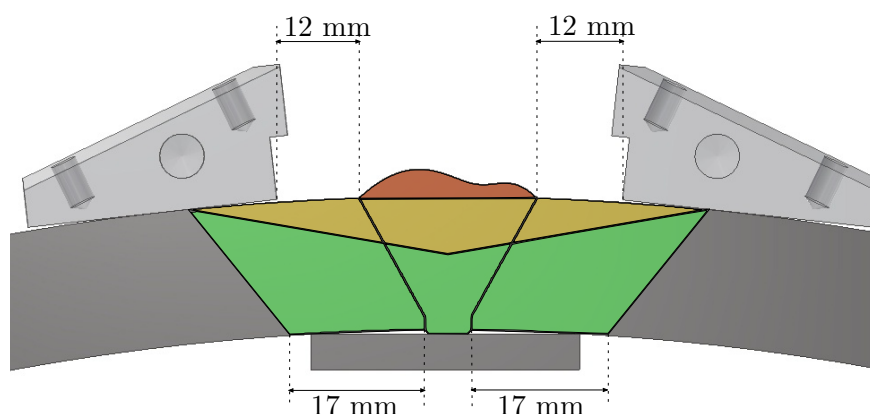


**Figure 5.17:** An overview of the inspection of weld A, showing a C-, S-, B- and A-scan respectively.

### 5.2.2 Scanning the Heat-Affected-Zone of Weld A

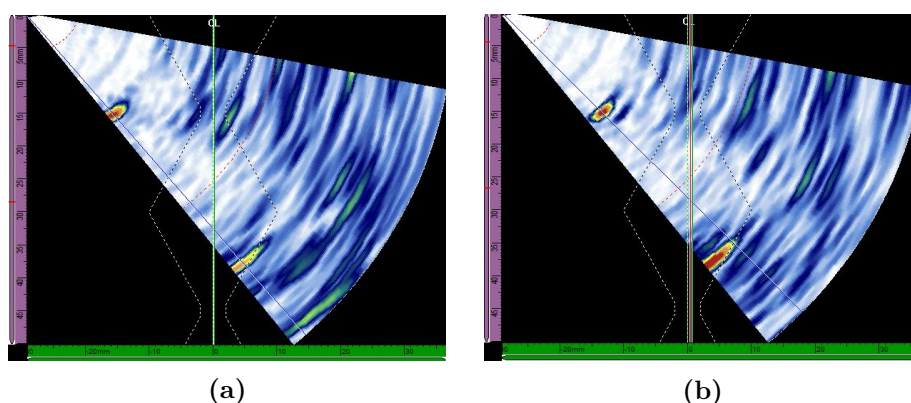
Because of the very limited time for PAUT weld inspection of the 11 T dipole prototype magnet a PAUT set-up was prepared before the half shell welds had been completed. Since the sensitivity calibration block was produced from the welds of the 11 T dipole, another sensitivity calibration was considered. This set-up was therefore calibrated for sensitivity on the 25 mm radius of calibration block No. 2. Because this calibration is not representative for the attenuating weld material, a larger general gain of 45 dB was applied after the angle-corrected-gain had been set.

This set-up was used to scan with the probes further apart, parallel to the weld and at 12 mm distance from the weld cap as shown in figure 5.18. It is called the "heat-affected-zone" scan because the probe position enables to scan the whole heat-affected-zone.



**Figure 5.18:** Cross-section illustration of the coverage of the weld volume for the 11 T dipole welds when the probes are placed 12 mm from the weld cap. The complete size of the heat-affected-zone is covered.

Two echoes from reflectors on the inner half shell surface was obtained and is shown in figure 5.19(a) and 5.19(b) located 15 mm and 13.5 mm away from the weld centreline respectively. Both signals had an amplitude of more than 100% FSH, compared to the root signal which had about 60% FSH. Because of the non-representative calibration for this PAUT set-up, it is not possible to use ISO 11666 to determine whether these indications are acceptable or not. They probably originate from pressure marks on the inner surface of the half shell or it could be slag products from the welding procedure. However, it is expected that signals like these will correspond to cracks which makes interpretation difficult.

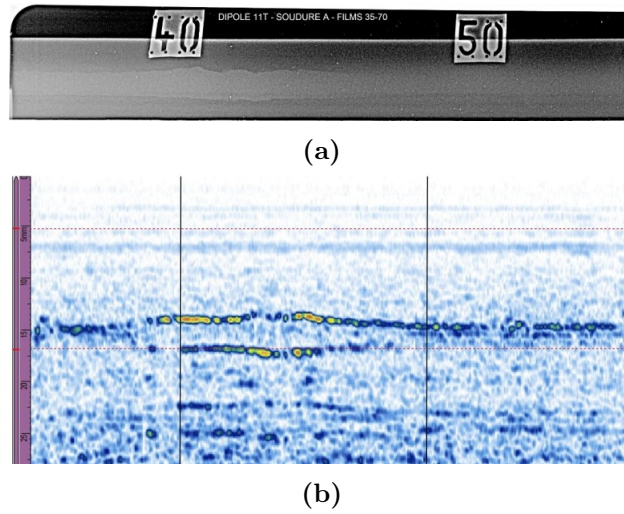


**Figure 5.19:** S-scans of two indications in the inner half shell surface in the heat-affected-zone at a distance of (a) 15 mm and (b) 13.5 mm from the weld centreline.

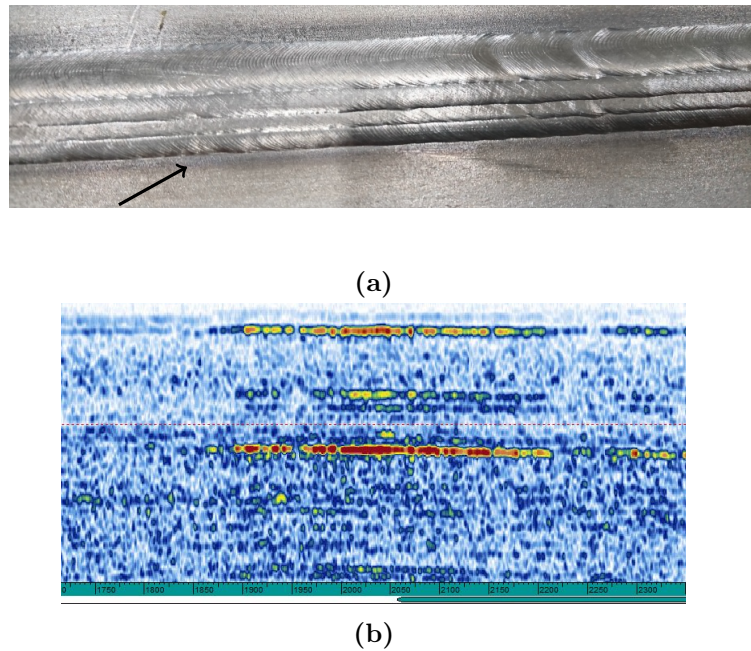
### 5.2.3 Scanning Selected Regions of Weld A at High Gain

Increasing the gain to a total of 45 dB enabled more analysis since the subtle amplitude differences becomes clearer. Noise and background signals are equally amplified, i.e. one cannot decide if the found indications are acceptable or not. However it is a cause for further testing of the region, maximizing the signal and perhaps using a different inspection method.

In a section of the weld, the root have melted significantly more than normal and fused to the backing plate at a wider area as shown in figure 5.20. A comparison between radiography and ultrasonic inspection is given. This feature of the weld is seen by both PAUT probes from both sides of the weld and is approximately 20 cm long.



**Figure 5.20:** The root has fused to a larger area of the backing plate,  $\approx 20$  cm. (a) Radiographic image. (b) Corresponding B-scan, the radiographic image show the area between the black lines.



**Figure 5.21:** (a) Picture of the surface with the surface-lack-of-fusion. The arrow indicate the clearest area, but the whole line is affected. (b) B-scan from the corresponding area.

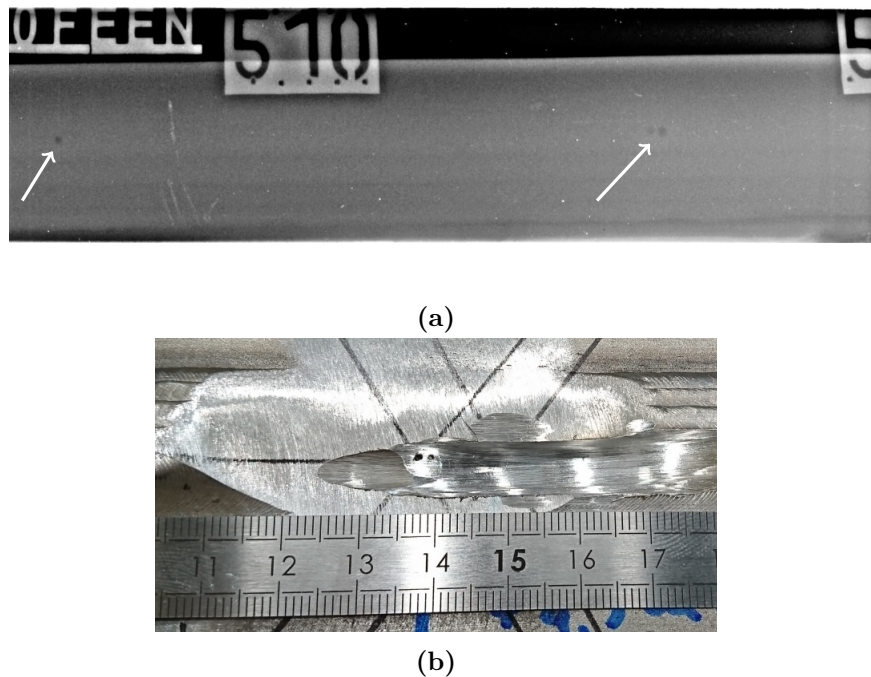
In another section of the weld, a surface-lack-of-fusion (surface-LOF), approximately 30 cm long was found, shown in and confirmed with a visual inspection shown in figure 5.21(a). The weld did not fuse completely with the parent material at the top surface, which show up clearly in the B-scan in figure 5.21(b). The arrow indicate the clearest spot but the whole line in the image has this surface-LOF. It was estimated to have a depth of  $<0.5$  mm.

#### 5.2.4 Scanning Selected Regions in Weld A where Radiography Revealed Pores

The PAUT set-up shown in figure 5.16 that was calibrated for sensitivity with the  $\varnothing = 2$  mm SDHs in the 11 T weld sample was used to inspect a region in weld A where a radiography revealed porosity shown in Figure 5.22(a). Their size were approximately 0.8 mm diameter, separated by less than 1 mm. Individually, the maximum size of a pore is 3 mm diameter according to ISO 5817, however since they are so close to each other, they must be considered as one, making this group of pores unacceptable.

This area of the weld was extensively tested with the PAUT set-up at a very large general gain setting to be able to distinguish the signal from the pores from the background noise, however unsuccessful. After the weld cap was grinded away an ultrasonic test using a 4 MHz longitudinal wave, dual element conventional probe at  $0^\circ$  showed that it is possible to detect pores of this size.

After grinding down to the location of the two closely lying pores, their depth below half shell surface was measured to 2 mm. The ultrasonic beam angle that is required to reach these pores with the PAUT set-up would be very large,  $>85^\circ$ , if inspected from the side of the ungrounded weld cap, at a sound path of approximately 25 mm. At such large angles there is large attenuation, resulting in bad signal to noise ratio making it hard to distinguish the signal. It may be possible to detect a pore of this size if the required ultrasonic beam angle is smaller.



**Figure 5.22:** (a) Radiographic image of region of weld A with pores. The single pore at the left side is acceptable. The two closely lying pores on the right form an unacceptable defect. (b) Two exposed closely lying pores 2 mm below shell surface.

### 5.2.5 Scanning Regions in Weld B where a Radiography Revealed Defects

A radiography of a region in weld B revealed three defects which could potentially be LOF, shown in figure 5.24(a). Since LOF is one of the most important type of defect to detect and characterize, this area was tested extensively both using the scanner and manually. The PAUT set-up calibrated on  $\varnothing = 2$  mm SDHs in the centreline of an 11 T dipole weld sample was used, however at a larger general gain of 40.5 dB.

When scanning the weld with probes parallel to the weld at a 2 mm distance from the weld cap as shown in figure 5.16 the defects were not detected. By skewing the probes by  $15^\circ$  as shown in figure 5.23, all three defects were detected in one scan as shown in figure 5.24(b). The dependency of probe angle to receive a strong ultrasonic echo is typical for a flat defect which suggest that the defects are in fact LOF or crack.



**Figure 5.23:** Top view illustration of one of the  $15^\circ$  skewed probe scans. The scanning direction is along the weld, i.e. up or down of the paper.

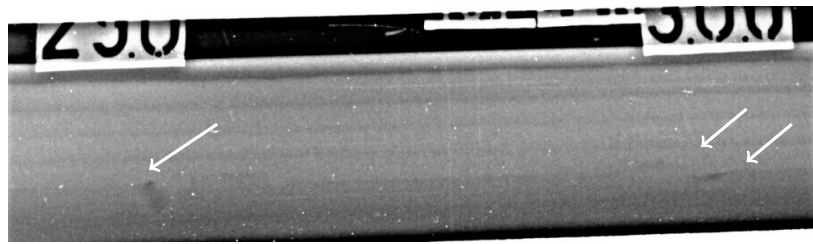
The root background signals are suppressed to much lower levels when skewing the probes compared to when scanning with probes parallel to the weld which enables the use of a higher gain without root signal interference. The noise was below 20% while the defects had a signal amplitude larger than 100% FSH which made them easy to distinguish. The defects were only detected by the probe from one side of the weld.

The measured depth of the defects by the PAUT set-up were 16 mm and 15 mm below surface. However due to the probe skew angle on the cylindrical surface, the positioning accuracy of this scan is estimated to  $\pm 2$  mm.

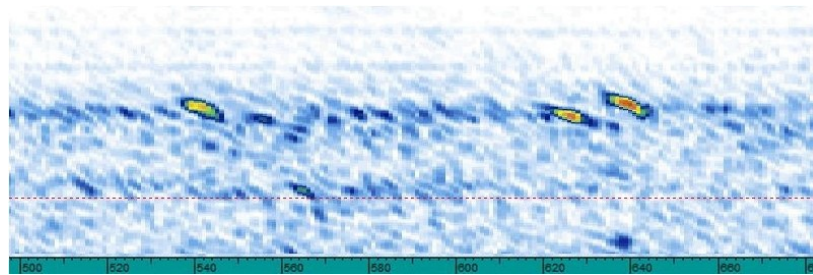
Because of the longer sound path distance to the weld region and the worse coupling to the cylindrical surface of the half shells in the skewed probe configuration, a larger general gain must be applied. The reference sensitivity level for acceptance level according to ISO 11666 is therefore not applicable. However, as these defects are suspected of being LOF or cracks which is not permitted according to ISO 5817, this scan can be used for determining areas which require further testing.

After the weld cap had been removed this area was inspected with one hand-held probe in order to maximize the signal from the defects. A signal amplitude of 190% FSH was obtained and noise less than 30% FSH.

Figure 5.24(c) show the exposed defects after grinding down the weld area. Their depths measured 15.1 mm and 14.2 mm below surface using callipers.



(a)



(b)



(c)

**Figure 5.24:** (a) Radiographic image between 290 cm and 300 cm of weld B showing three defects, presumably LOF. (b) B-scan of the same weld volume where the defects appear at the same position. A different point of origin was chosen compared to the radiography. (c) Photography of the exposed defects after grinding down the weld area.

### 5.3 Discussion of the Results of PAUT of the 11 T Dipole Magnet Welds

The developed scanner for the inspection of the 5.5 m long horizontal austenitic stainless steel welds of the 11 T dipole magnets enables the simultaneous operation of two PAUT probes that are aligned to the weld. The scanner allows easy access to the probes and flexible adjustments of probe position and angle for non-standard test configurations. An encoder for length sizing and water couplant ports are integrated into the scanner to simplify the inspection.

Dedicated sensitivity calibration weld samples with artificial defects (side-drilled-holes) have been designed and produced from 11 T dipole prototype austenitic stainless steel half shell welds. These provide representative calibration for the strongly attenuating and scattering austenitic stainless steel weld material. The developed calibration station allows for well reproducible and efficient sensitivity calibration before and during the PAUT inspections. The calibration blocks can be used as reference for locating, sizing and characterizing defects and especially volume defects such as pores, cavities or inclusions.

Reference weld samples with FBHs and notches have been designed and produced from 11 T dipole prototype austenitic stainless steel half shell welds and are used for locating and sizing flat defects such as cracks and lack-of-fusion in the weld bevel.

The PAUT focal law determined in chapter 4 was used to inspect all of the reference weld samples. All artificial defects were detected with the probe on either side of the weld in two scans, one with the probes placed parallel to the weld at 2 mm distance from the weld cap (figure 5.16), and one scan with the probes placed parallel to the weld but at 12 mm from the weld cap (figure 5.18). These two scans completely cover the weld volume, including the entire weld bevel, and the heat-affected-zone. The routine non-destructive testing with these two PAUT scans is thus sufficient to fulfil the requirements of weld quality level B in ISO 5817 [11].

The radiographic examination of the welds of the first 11 T dipole prototype magnet revealed defects that could not be detected with the PAUT inspection using only these two scans, but two additional scans were needed. One where the probes are skewed by  $+15^\circ$ , and another where the probes are skewed by  $-15^\circ$  (figure 5.23). This way the natural defects were clearly detected using the same PAUT set-up as for the two scans with probes parallel to the weld. However this is a further quality control beyond the standard requirements.

So, even though the standards state that two scans are sufficient for the control of the welds using PAUT, some non-conforming defects can go undetected. Every non-destructive testing method has advantages and disadvantages where certain defects in their configuration, can or cannot be detected. For the PAUT this is true for the undetected natural defects in the 11 T dipole weld where three defects were oriented in such a way that the normal scans were unsuccessful and a skewed probe position were required. Radiography has a better resolution than PAUT and can detect smaller defects as demonstrated for the two shallow and closely lying pores which the PAUT was unable to detect from either side of the weld cap.

Compared to radiography which is using ionizing radiation, PAUT is a much safer inspection method by using ultrasound instead. Radiography require access to both sides of the weld where the penetrating radiation projects an image onto a photographic film on the backside which then can be developed and analysed. PAUT on the other hand require access to only one side and can determine the depth position of the defects, not only provide a projection of the weld. However, sensitive equipment must be protected by water-spill. Both techniques can be used for the quality control of the 11 T dipole weld and it must be decided which techniques advantages and disadvantages outweighs the other.

Due to the anisotropy of the weld material, shown in chapter 4, the sound beam is differently attenuated, scattered and diverted when measuring on either side of the weld. This is most clearly shown in the weld samples which have artificial defects symmetrically around the weld centreline. For example, the SDHs in the centreline of the 11 T dipole weld sample where a difference of 70% FSH (151%-81%) was obtained when measuring the bottom SDHs from either side. As a comparison the signal amplitude from the bottom SDH in the fusion line weld sample was 114% where the beam does not pass through any weld material and has similar sound path. This anisotropy causes a sensitivity calibration uncertainty.

Approval of the test procedure for the non-destructive testing of the 11 T dipole welds needs to be done by an expert with level 3 expertise (table 5.1) within ultrasonic testing according to *ISO 9712 - Non-destructive testing - Qualification and certification of NDT personnel* [56]. Personnel with expertise of level 2 can perform the routine tests, analyse the data and report the results.

**Table 5.1:** Minimum requirements for level certification for ultrasonic testing. [56]

|                       | <b>Level 1</b> | <b>Level 2</b> | <b>Level 3</b> |
|-----------------------|----------------|----------------|----------------|
| Training              | 40 hours       | 80 hours       | 40 hours       |
| Industrial experience | 3 months       | 9 months       | 18 months      |



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# 6

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## CONCLUSION

A test setup for the non-destructive testing of the 11 T dipole horizontal welds by PAUT has been developed and commissioned. A scanner that allows to control the welds in a well-defined and reproducible test geometry with two phased array probes aligned to the 5.5 m long horizontal welds has been designed and built.

Dedicated calibration and reference blocks with artificial defects have been developed and produced. Different focal laws have been compared, and the sensitivity to detect different defect types has been determined.

One scan with two phased array probes aligned parallel to the weld in 2 mm distance from the weld cap edge, and one scan with the probes aligned parallel to the weld in 12 mm distance from the weld cap edge are sufficient to show if the inspected welds fulfil the requirements of weld quality level B according to ISO 5817 [11].

The standard test duration for the two scans of the two 5.5 m long horizontal welds of the 11 T dipole magnets is about one day, provided that no defects are found that need to be characterized in more detail.

Some natural defects were only seen with two additional scans, one with  $+15^\circ$  and one with  $-15^\circ$  skewed probes in relation to the weld.

The ultrasonic inspection can be much more sensitive and efficient if the weld cap is removed prior to the weld inspection, so that a direct detection of the entire weld volume with a single ultrasound probe is possible. This can be exploited to examine in more detail defects that have been revealed by the PAUT test.

In order to assure a good coupling of the wedges to the steel shells, on 5 cm on either side of the welds surface irregularities like tack-welds, weld projections and pressure marks must be removed prior to the weld inspection. Water is used as coupling medium, and the surrounding equipment must be protected from water spill.

According to ISO 9712, level 2 certification is required for the non-destructive testing of the pressure vessel welds by phased array ultrasonic testing, and level 3 certification is required in order to approve the test procedure, set-up and equipment [56].



# Appendices



# A

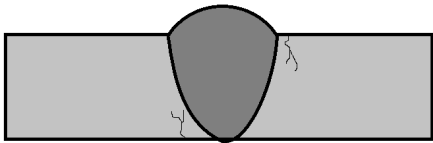
## WELD QUALITY AND TESTING REQUIREMENTS

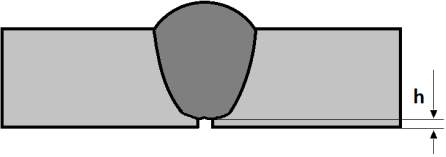
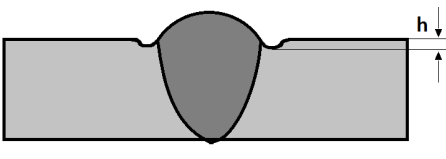
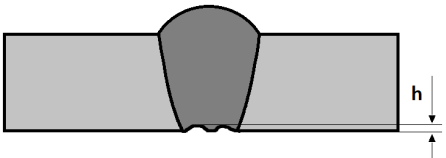
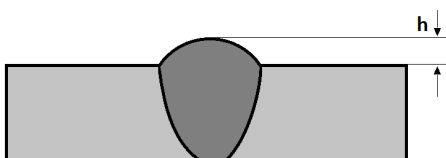
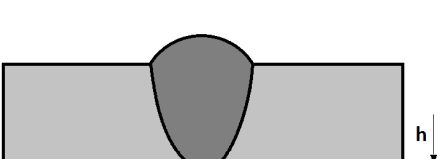
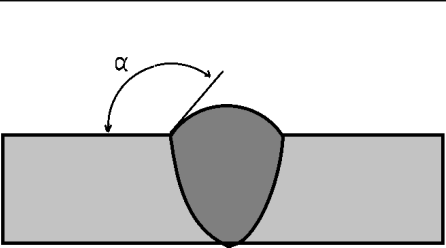
### A.1 Quality Levels

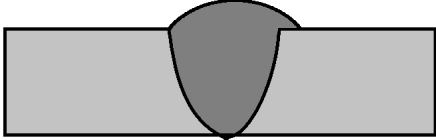
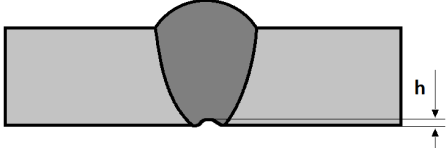
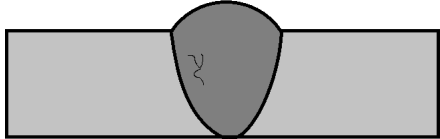
Table A.1 show different types of defects that can occur in a weld and states the maximum size of the different types of defects that can be accepted according to quality level B in *ISO 5817: 2003(E) Welding Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) Quality levels for imperfections* [11]. Consideration to the 15 mm thick V-butt weld has been made. Visual testing (VT) is performed first by looking at the weld, where surface imperfections can be identified without using ultrasonic testing (UT).

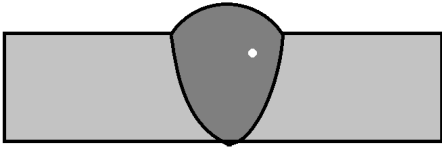
**Table A.1:** Limits for imperfections.

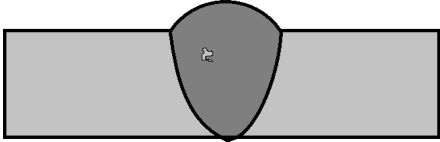
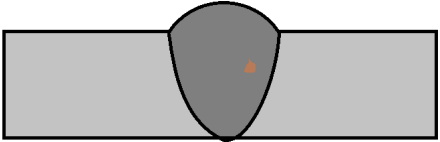
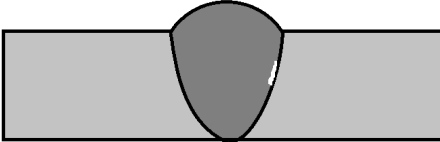
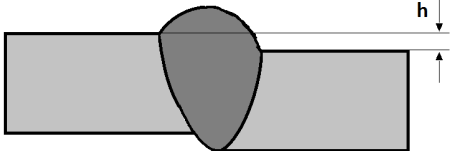
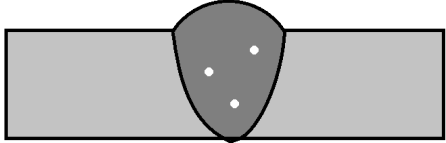
"h" stands for thickness or width of the defect in question and "l" stands for length of the defect if applicable. Within 100 mm of the weld where the number of imperfections are the greatest; if the total length of these imperfections are less than 25 mm they are considered short imperfections. The evaluation area or projected area of the weld referred in 2.2-2.4 and 4.2 is approximately taken as 100x20mm. [11]

| Imperfection Designation     | Remarks                                                                             | Quality Level B | Inspect. Method |
|------------------------------|-------------------------------------------------------------------------------------|-----------------|-----------------|
| <b>Surface Imperfections</b> |                                                                                     |                 |                 |
| Crack                        |  | Not permitted   | VT, UT          |
| Crater crack                 |                                                                                     | Not permitted   | VT              |
| Surface pore                 |                                                                                     | Not permitted   | VT              |
| End crater pipe              |                                                                                     | Not permitted   | VT              |
| Lack of fusion               |                                                                                     | Not permitted   | VT, UT          |

| Imperfection Designation                      | Remarks                                                                             | Quality Level B                        | Inspect. Method |
|-----------------------------------------------|-------------------------------------------------------------------------------------|----------------------------------------|-----------------|
| Incomplete root penetration                   |    | Not permitted                          | UT              |
| Continuous undercut and intermittent undercut |    | $h \leq 0.5mm$                         | VT              |
| Shrinkage groove                              |   | Short imperfections:<br>$h \leq 0.5mm$ | UT              |
| Excess weld metal                             |  | $h \leq 3mm$                           | VT              |
| Excess penetration                            |  | $h \leq 2mm$                           | UT              |
| Incorrect weld toe                            |  | $\alpha \geq 150^\circ$                | VT              |

| Imperfection Designation          | Remarks                                                                                                                                           | Quality Level B                             | Inspect. Method |
|-----------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------|-----------------|
| Overlap                           | Weld material that has spilled over to the side of the weld<br>  | Not permitted                               | VT              |
| Sagging, Incomplete filled groove | Weld material does not fill the area up and above the surface of the plate. Compare with Root concavity.                                          | Short imperfections:<br>$h \leq 0.5mm$      | VT              |
| Burn through                      |                                                                                                                                                   | Not permitted                               | VT              |
| Root concavity                    |                                                                 | Short imperfections:<br>$h \leq 0.5mm$      | UT              |
| Root porosity                     | Spongy formation at the root of a weld due to bubbling of the weld metal at the moment of solidification (e.g. lack of gas backing)               | Not permitted                               | UT              |
| Poor restart                      |                                                                                                                                                   | Not permitted                               | VT              |
| Stray arc                         |                                                                                                                                                   | Not permitted                               | VT              |
| Spatter                           |                                                                                                                                                   | Acceptable, but must be removed before PAUT | VT              |
| <b>Internal imperfections</b>     |                                                                                                                                                   |                                             |                 |
| Cracks                            | All types of cracks except micro cracks and crater cracks.<br> | Not permitted                               | UT              |

| Imperfection Designation                  | Remarks                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Quality Level B                              | Inspect. Method |
|-------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------|-----------------|
| Gas pore - uniformly distributed porosity | <p>The total area of uniformly distributed pores in a projected area of the weld must be lower than 1%. 15 pores with 1 mm diameter in a 12 cm<sup>2</sup> area correspond to approximately 1%. Systematic imperfections included in the total imperfection area.</p> <p>Maximum dimension for a single pore</p>                                                                                            | $\leq 1\%$ or 3mm                            | UT              |
| Clustered (localized) porosity            | <p>If the pores are clustered one draw a circular area tight around the cluster which will be the collective pore area. The sum of such areas in the projected evaluation area of the weld must be smaller than 4%. If the distance between two such areas is smaller than the smallest area of one of the two clusters an envelope around the two must be included in the total imperfection area. Also inclusive of systematic imperfections.</p> <p>Maximum dimension for single pore</p> | $\leq 4\%$ or 2mm                            | UT              |
| Linear porosity                           | <p>In the projected evaluation area of the weld, the sum of the areas of the pores lying on a line must be smaller than 2% inclusive of the areas of systematic imperfections. If the distance between two pores is smaller than the diameter of the smallest neighboring pore the envelope area of the two pores must be included.</p> <p>Maximum dimension for single pore</p>                                                                                                             | For single layer: $\leq 2\%$ or 2mm          | UT              |
| Elongated cavity wormholes                |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | $h \leq 2\text{mm}$<br>$l \leq 15\text{ mm}$ | UT              |
| Shrinkage cavity                          |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Not permitted                                | UT              |
| Crater pipe                               | A small pipe occurring when one seam stop and later overrun by another.                                                                                                                                                                                                                                                                                                                                                                                                                      | Not permitted                                | UT              |

| Imperfection Designation                    | Remarks                                                                                                                                                                                                                  | Quality Level B                                                     | Inspect. Method |
|---------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------|-----------------|
| Inclusions                                  | Solid inclusions, Slag inclusions, flux inclusions and oxide inclusions<br>                                                             | $h \leq 2\text{mm}$<br>$l \leq 15\text{ mm}$                        | UT              |
| Metallic inclusions other than copper       |                                                                                                                                                                                                                          | $h \leq 2\text{mm}$                                                 | UT              |
| Copper inclusions                           |                                                                                                                                         | Not permitted                                                       | UT              |
| Lack of fusion                              | In these three areas: <ul style="list-style-type: none"> <li>• Side wall, see figure</li> <li>• Inter-run</li> <li>• Root</li> </ul>  | Not permitted                                                       | UT              |
| <b>Imperfections in joint geometry</b>      |                                                                                                                                                                                                                          |                                                                     |                 |
| Linear misalignment                         |                                                                                                                                       | $h \leq 1.5\text{mm}$                                               | VT              |
| <b>Multiple imperfections</b>               |                                                                                                                                                                                                                          |                                                                     |                 |
| Multiple imperfections in any cross section |                                                                                                                                       | Maximum total height of imperfections<br>$\Sigma h \leq 3\text{mm}$ | Not applicable  |

| Imperfection Designation                                    | Remarks                                                                                                                                                                                                                                                                                                                                                          | Quality Level B         | Inspect. Method |
|-------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------|-----------------|
| Projected or cross sectional area in longitudinal direction | The area of each imperfection is taken as the length $l$ times the width $h$ and then sum up all of these. This area must be smaller than 4% of the projected area of the weld. If the distance between two imperfections are smaller than the smallest length of one of the neighboring imperfections one must also add the area between the two imperfections. | $\Sigma h * l \leq 4\%$ | Not applicable  |
|                                                             |                                                                                                                                                                                                                                                                                                                                                                  |                         |                 |

## A.2 Acceptance Levels

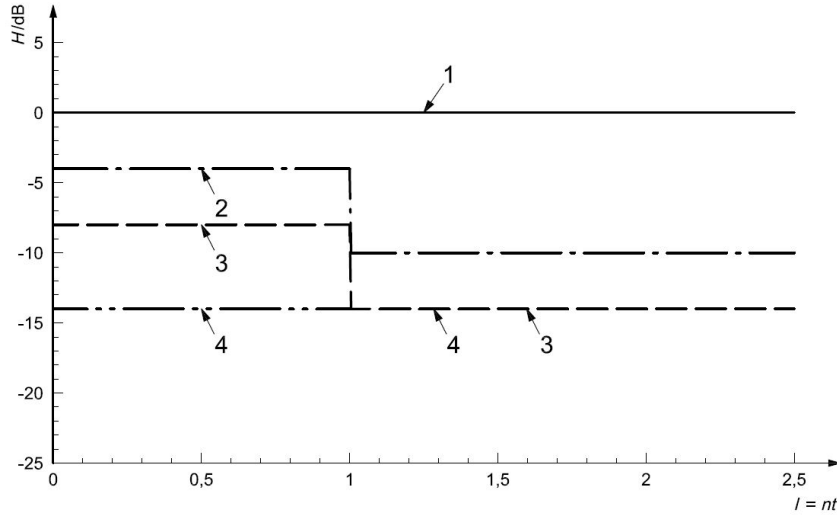
Due to the difficulties of characterizing found defects with ultrasonic inspection there is a second standard, *ISO 11666 - Non-destructive testing of welds - ultrasonic testing - Acceptance levels* [12], which is used for determining whether the found defect is acceptable or not. It is fully customized after the ultrasonic inspection features and limitations but does not consider characterization of defects. It basically serves as a link between the quality levels found in table A.1 and inspection data. This standard is summarized below with regards to the 15 mm thick austenitic stainless steel half shells, ultrasonic equipment including type of probe and wedge and the use of calibration blocks with side drilled holes and notches. From *ISO 17635 - Non-destructive testing of welds - General Rules for metallic materials* [55], quality level B require acceptance level 2.

### A.2.1 Amplitude of Echoes from Imperfections

Figure A.1 shows the different levels that needs to be considered in the signal output when testing the welds. The reference level,  $H_0$ , is calibrated using one or several sensitivity calibration blocks with artificially created defects at defined positions.

The resulting signal amplitudes from these defects are used to calculate an appropriate reference level. Imperfections in the test object giving a maximum amplitude larger than the evaluation level (4) needs to be considered and evaluated carefully, where the length of the imperfection is taken as the length where the signal amplitude is above the evaluation level. Imperfections yielding a response larger than the acceptance level (2) is unacceptable, i.e. the weld has to be repaired. Imperfections yielding a response smaller than the acceptance level (but higher than the evaluation level) with a length longer than 15 mm must be tested in greater detail as seen in figure A.1 due to the drop in acceptance level.

1. **Reference level:**  $H_0$
2. **Acceptance level:** Defect length  $< 15mm \rightarrow H_0 - 4dB$   
Defect length  $> 15mm \rightarrow H_0 - 10dB$
3. **Recording level:** Defect length  $< 15mm \rightarrow H_0 - 8dB$   
Defect length  $> 15mm \rightarrow H_0 - 14dB$
4. **Evaluation level:**  $H_0 - 14dB$



**Figure A.1:** Acceptance level diagram with respect to defect length [12].

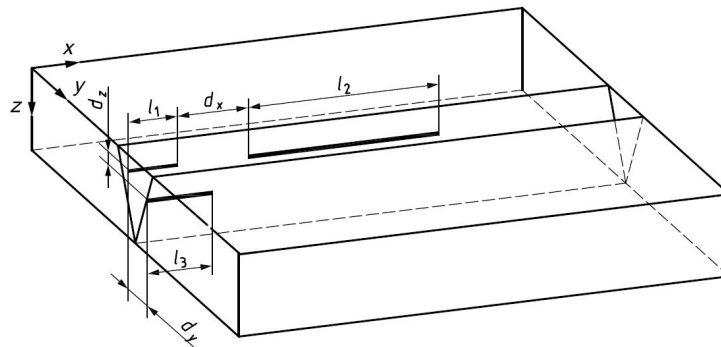
### A.2.2 Grouping of Closely Lying Imperfections

In addition, individually acceptable imperfections with amplitude larger than the recording level are being grouped together if the distance between the two imperfections are smaller than a specified value, different depending on direction, see figure A.2. The grouped imperfections are then again assessed towards figure A.1 using the maximum amplitude of the two and with the total combined length. The length of a group shall not be used for further grouping.

Two imperfections are grouped if:

- a)  $d_x$  is less than twice the length of the longer indication
- b)  $d_y$  is smaller than 7.5 mm
- c)  $d_z$  is smaller than 7.5 mm

Example:  $l_1$  and  $l_2$  are too close, then the combined length is  $l_{12} = l_1 + l_2 + d_x$

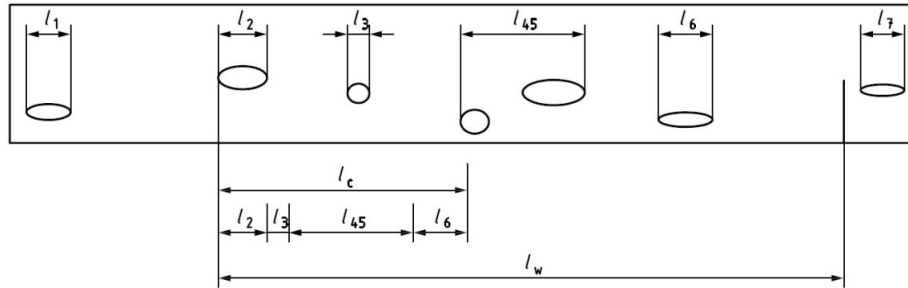


**Figure A.2:** Grouping of closely lying imperfections. [12]

### A.2.3 Limits of the Total Length of Acceptable Indications in a Weld Section

The total cumulative length,  $l_c$ , of all acceptable indications, individual or grouped, in any  $l_w = 90$  mm section of the weld, cannot exceed 20%, see figure A.3. This length is given by all single

indications and all grouped indications with amplitude larger than the recording level that is linearly aligned. In other words, one does not include the length of an indication "behind" the other.



**Figure A.3:** Cumulative length of acceptable indications cannot exceed 20%. [12]

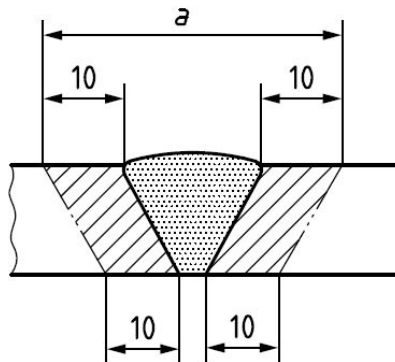
### A.3 Testing Techniques and Testing Level

In this section a summary of the testing level and testing techniques as described in *ISO 17640 - Non-destructive testing of welds - Ultrasonic testing - Techniques, testing level, and assessment* [13], with regards to the thickness of the weld material and ultrasonic equipment is summarized. Quality level B require a testing level of at least B according to *ISO 17635* [55].

#### A.3.1 Testing Volume and Scanning Surface

The testing shall cover both the weld and the parent material in the heat affected zone with a minimum of 10 mm on both sides of the weld. A.4 below show a cross section of the minimum testing volume.

The scanning surfaces on the half shell tubes must be smooth and free from dirt and other foreign material that is likely to interfere with the measurement, especially the wedge-surface coupling. In this case weld spatter, notches or grooves in the surface are most common, others are loose scales and rust (for mild steel) which has to be removed.



**Figure A.4:** Minimum testing volume including the heat affected zone. [13]

### **A.3.2 Range and Sensitivity Settings**

The range and sensitivity calibration is performed using the techniques of side-drilled-holes in one or several specifically designed calibration blocks, and on a standard calibration block. Checks to confirm the settings shall be performed every 4 hours of testing and at completion of the testing on the same blocks. If a system parameter has changed during the test additional checks must be done.

If the sensitivity checks reveal a deviation  $\leq 4$  dB the sensitivity setting must be corrected before continuing testing. However, if the check show a deviation  $> 4$  dB, the setting must be corrected and the testing performed after the previous check has to be repeated. The same goes for range calibration where a range deviation of  $\leq 2\%$  shall be corrected before continuing testing. Deviations  $> 2\%$  must be corrected and the previous testing period must be repeated.

### **A.3.3 Probe Position**

Two probe positions are required, one on either side of the weld. If only one side is accessible, two probe angles must be used. The probe position in the axial direction must be recorded in relation to a reference point on the test piece. The reference point makes it possible to introduce a coordinate system where any imperfections in the material can be located.

Since two probes are used simultaneously on both sides of the weld there is no need to use different probe angles, although more angles and/or probe positions will provide more information which could help in the analysis of the PAUT data. By placing the probe wedges with the front face parallel to the weld axis and as close to the weld crown as possible one can ensure that the whole weld volume is covered.



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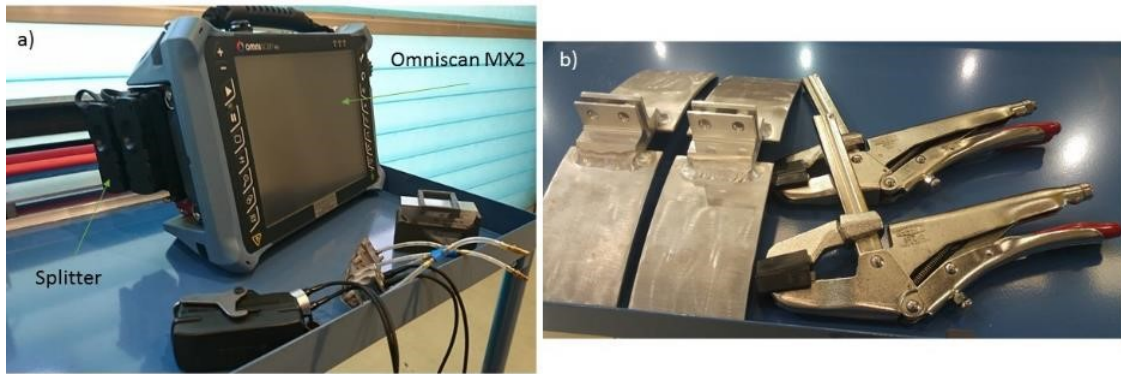
# B

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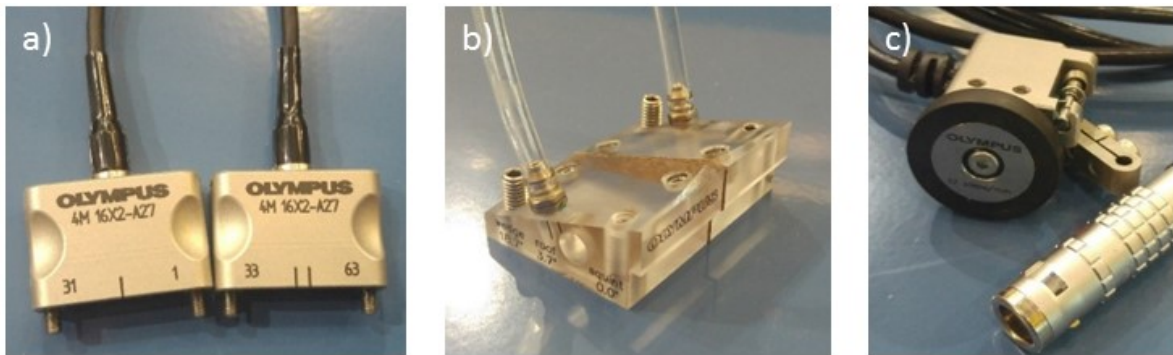
## PAUT EQUIPMENT FOR 11 T DIPOLE WELD INSPECTION

### B.1 Main PAUT Equipment

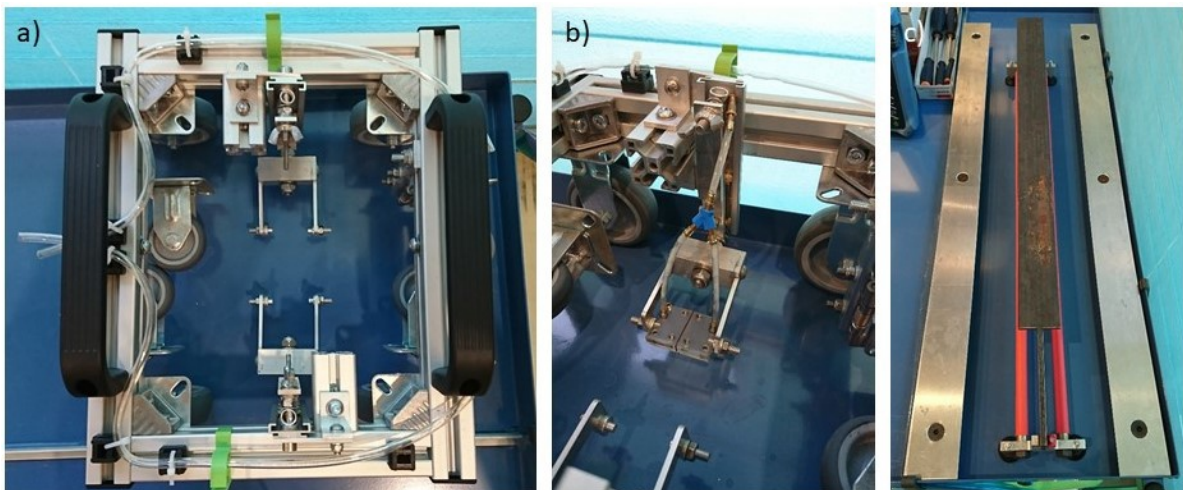
- Omniscan MX2 phased array flaw detector, shown in figure B.1 (a)
- 1 Splitter, Omni-A2-Split128, for connecting 2 probes to the Omniscan, shown in figure B.1 (a)
- 2 sets of PAUT probes, DMA-4M-16X2-A27, Olympus, shown in figure B.2 (a)
- 2 PAUT wedges, SA27-DN55L-FD15-IHC, with 18.7 wedge angle for DMA probes, shown in figure B.2 (b)
- 1 Mini-wheel encoder for length encoding of the acquired PAUT data, shown in figure B.2 (c)
- 1 Scanner for double sided PAUT inspection of the horizontal welds of the 11 T dipole, shown in figure B.3 (a) and figure B.3 (b)
- 1 Calibration station for calibration of the PAUT set-up while using the scanner, shown in figure B.3 (c)
- 1 CFU-05 couplant feed unit, water tank, inlet tube with a filter and outlet tube, shown in figure B.4
- 2 T-bar holders for mounting a T-bar on top of the 11 T dipole magnet, shown in figure B.1 (b)
- 4 clamps to fix the T-bar holders on top of the 11 T magnet, shown in figure B.1 (b)
- 2 Aluminium T-bars, 6.5 m long, 50 mm height, 50 mm width and 5 mm material thickness
- 1 Power cable drum with 4 outlets (30 m)
- 2 bottles Ultrasonic Gel, Ultragel II, Controltech
- 1 Trolley for transport of the PAUT equipment



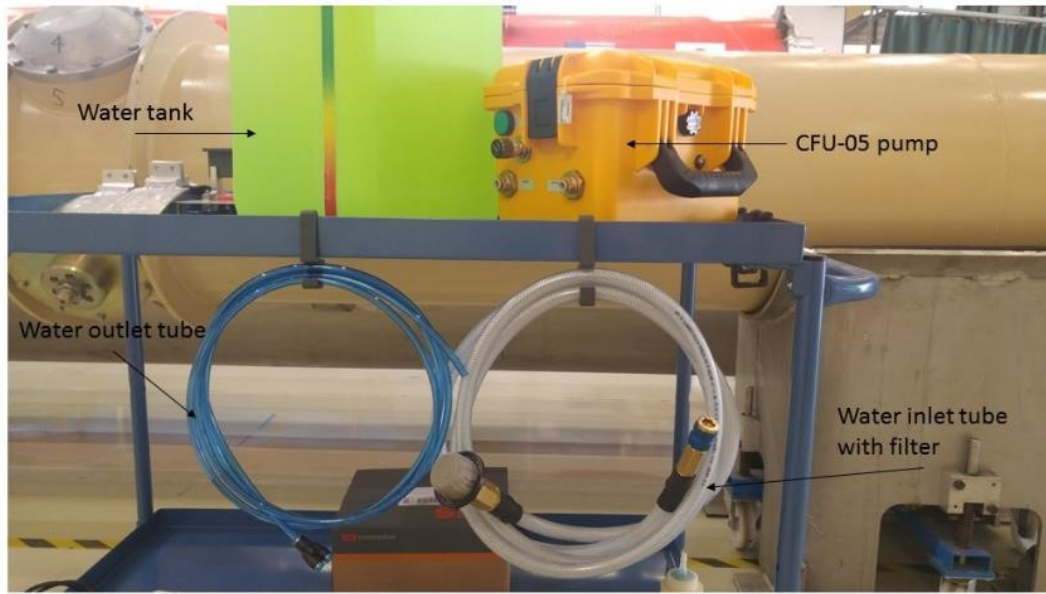
**Figure B.1:** (a) Omniscan MX2 phased array flaw detector. The splitter, Omni-A2-Split128, connected to the phased array port. (b) T-bar holders and clamps



**Figure B.2:** (a) 1 set of PAUT probes, DMA-4M-16X2-A27. (b) 1 PAUT wedge, SA27-DN55L-FD15-IHC  
c) The mini-wheel linear encoder



**Figure B.3:** (a) Top view of the scanner. (b) Wedge holder mounted in the scanner. (c) Calibration station.

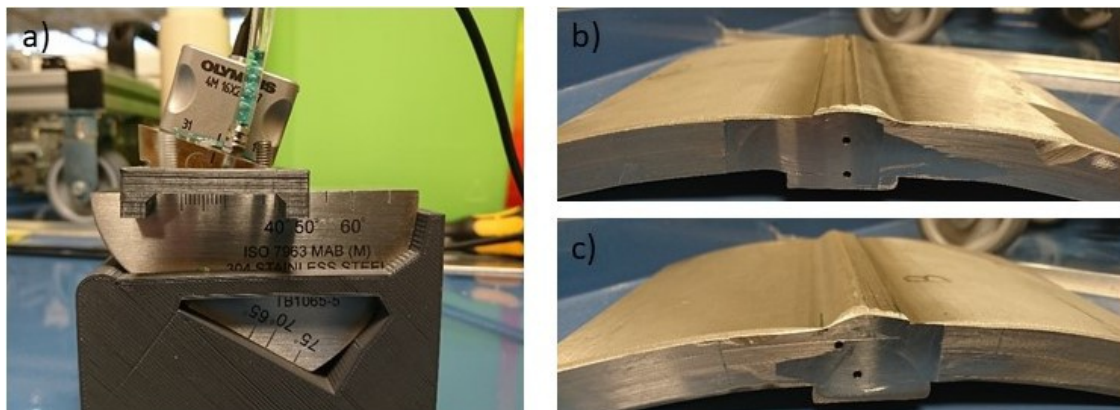


**Figure B.4:** CFU-05 couplant feed unit with water tank, water inlet tube with water filter and a water outlet tube.

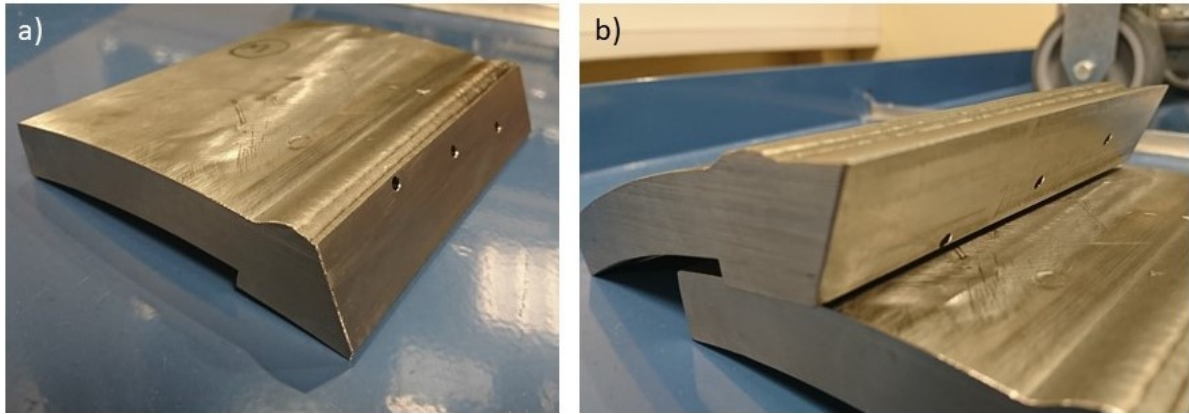
## B.2 11 T Dipole Weld Calibration and Reference Samples

The extending half shell welds which is removed from the first 11 T dipole prototype magnet was used to produce sensitivity calibration and reference weld samples. The 15 mm thick 316LN austenitic stainless steel weld samples were machined with artificial defects, side-drilled-holes, notches and flat-bottomed-holes.

- 1 range calibration block, No. 2, figure B.5 (a)
- 1 sensitivity calibration block, Centreline SDH, figure B.5 (b). (On the other edge of this block, 3 sensitivity reference notches have been machined)
- 1 sensitivity reference block, 12 cm long, Fusion line SDH, figure B.5 (c)
- 1 sensitivity reference block, 12 cm long, Indirect FBH, figure B.6 (a)
- 1 sensitivity reference block, 12 cm long, Direct FBH, figure B.6 (b)



**Figure B.5:** (a) Range calibration block "No. 2" with 3D printed holder and wedge aligner. The probe is placed on top of the block. (b) The "Centreline SDH" sensitivity calibration weld sample with side-drilled-holes and notches. (c) The "Fusion line SDH" sensitivity reference weld sample with side-drilled-holes.

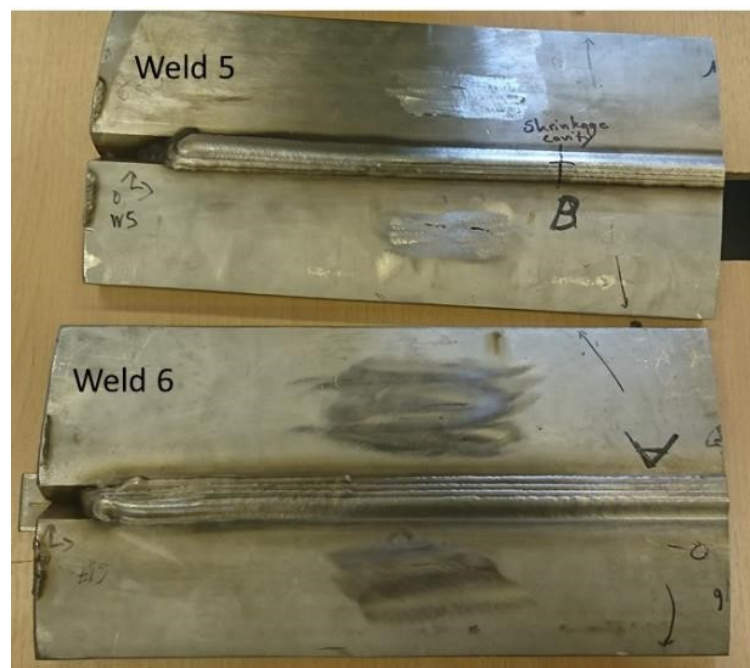


**Figure B.6:** (a) The "Indirect FBH" reference weld sample with flat-bottomed-holes (b) The "Direct FBH" reference weld sample with flat-bottomed-holes.

### B.3 11 T Dipole Weld Samples

Two weld samples from the first 11 T dipole prototype magnet were not machined but can be used to create new reference samples.

- 1 weld sample, 35 cm long, "Weld 5", figure B.7. This block has a natural defect, presumably a shrinkage cavity in the root
- 1 weld sample, 35 cm long, "Weld 6", figure B.7

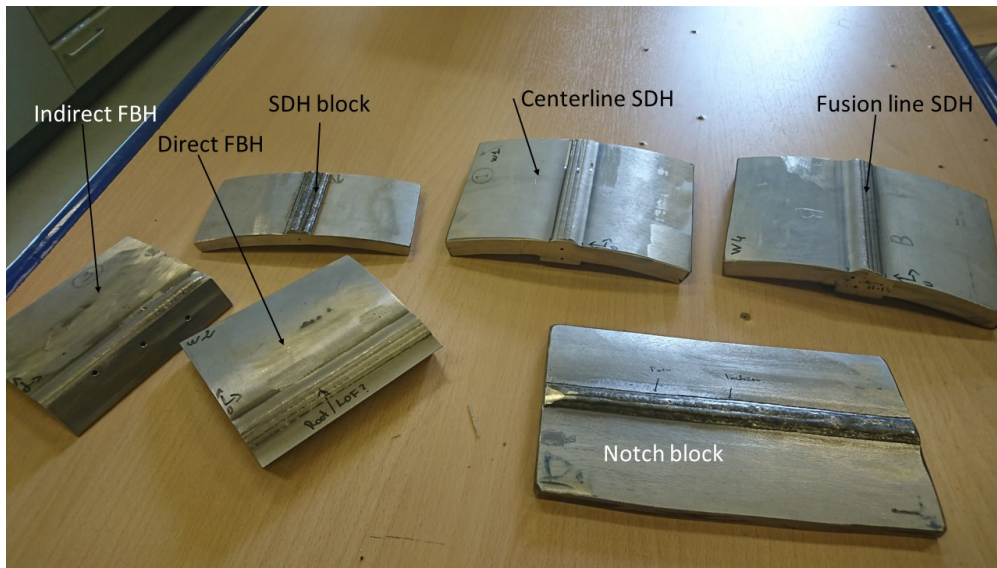


**Figure B.7:** "Weld 5" and "Weld 6" of 11 T dipole weld.

## B.4 Other magnet austenitic stainless steel shell weld samples

These weld samples from an LHC main dipole have a MIG weld in 10 mm thick austenitic stainless steel half shells, no backing plate. These samples have been machined with artificial defects, side-drilled-holes and root notches.

- 1 weld sample, 7 cm long, SDH block, figure B.8
- 1 weld sample, 20 cm long, Notch block, figure B.8



**Figure B.8:** The two LHC main dipole weld samples are marked with "SDH block" and "Notch block". The four calibration and reference weld samples from the 11 T dipole is also shown.

## B.5 16 mm Thick Austenitic Stainless Steel Flat Weld Sample

This 40 cm long and 16 mm thick sample (figure B.9) has five weld areas where artificial defects have been machined in the parent material. (side-drilled-holes and notches)

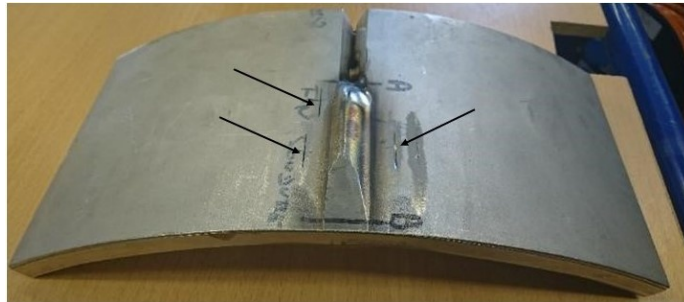


**Figure B.9:** Flat sample with artificial defects machined in five different "weld areas".

## B.6 11 T Single Aperture Short Model Weld Samples

These weld samples from an 11 T single aperture short model are TIG welded and has a backing plate. The austenitic stainless steel half shells are 12 mm thick and the samples has not been machined with artificial defects.

- 1 weld sample, 13 cm long, with 3 surface notches, figure B.10
- 4 weld samples, 13 cm long, figure B.11



**Figure B.10:** 1 weld sample from an 11 T single aperture short model with 3 surface notches.



**Figure B.11:** 4 weld samples from an 11 T single aperture short model without any artificial defects.

## B.7 Tools and Attachments

- 2 adjustable spanners
- 1 set of Hex-keys
- 1 set of Hex-keys with handles
- 1 Phillips screwdriver
- Attachments for modifications of the scanner
  - Screws, lock nuts and washers in M3, M4, M5 and M6 in various sizes.
  - M6 wing nuts

- M5 aluminium profile attachments
- 4 types of compression springs for wedge holder

## B.8 Miscellaneous Items

- 1 Steel T-bar, 1.8 m long, 50 mm height, 50 mm width and 6 mm material thickness for PAUT inspection of horizontal welds on 11 T short models.
- 3D-printed parts
  - 1 calibration block No. 2 holder with separate piece for wedge alignment, Figure 42 (a)
  - 7 hooks for trolley in 2 sizes (grey)
  - 6 aligners for aluminium T-bar (white)
  - 3 block aligners for steel T-bar (grey)
  - 1 drainage funnel (green)
- 1 spool transparent water tube, 4 mm inner diameter
- 1 bucket
- 1 blue paper roll
- 8 rolls of plastic bags
- 1 roll of red heat shrink tube
- 1 roll white duct tape



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