

# Immersion Ultrasonic Testing on EUROFER Welded Joints for Determination of the Minimum Detectable Flaw Size

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**Abstract:** The ferritic-martensitic steel EUROFER is intended for use as a structural material for blanket components of future fusion reactors. A blanket module consists of a multiplicity of diffusion-welded cooling plates, which are connected by TIG, EB or laser welding seams. For the quality assurance of these welding seams the ultrasonic non-destructive testing is currently examined. In the context of this work the ultrasonic immersion testing is considered for the examination of EUROFER parts including welding seams of different types (diffusion welding, electron-beam welding and TIG - welding). Differently arranged artificial flaws of varying sizes were introduced into the welding seams to determine their minimum detectable size. In essence, the artificially introduced flaws for immersion testing consisted of longitudinal holes and cross holes 0.2 mm to 1.0 mm in diameter as well as of tungsten wires whose diameter was in the range of 0.2 mm to 1.0 mm. Investigations were conducted using the KC 200 immersion testing facility developed by GE Inspection Technologies. Ultrasonic testing was performed intermitting straight- and angle beam examinations of longitudinal and transverse waves from sensors of different resolutions. The DAC (Distance Amplitude Correction) curves for flaws that are 0.2 mm and 0.1 mm in diameter were derived from the measuring results in addition.

## 1. Introduction

In blanket modules, e. g. the EU Test Blanket Modules (TBMs), the low activation steel like EUROFER 97 will be used as structural material. The first wall and cooling plates with cooling channels will be welded by Hot Isostatic Pressing (HIP), and the stiff grids are expected to be welded by Electron-Beam (EB) or Tungsten Inert Gas (TIG). Welded structures can fail catastrophically if they contain cracks above a certain critical size for the load applied. Development of a Non-Destructive Testing (NDT) method to detect the cracks in the welded area is one of the key issues in developing plasma-facing components (PFCs) for next generation fusion devices.

Ultrasonic testing is one of the mostly applied procedures in non-destructive materials testing (NDT). It is used for examination of welds, castings, automotive components, pressure vessels, etc. Non-destructive testing is one of the most important methods of safety monitoring. The aim of the NDT is to find in the considered components in-homogeneity or defects without their destruction and to evaluate the test results so that a decision can be made for the applicability of these components.

The ultrasonic method has a tradition of more than four decades. Very first examinations using ultrasonic oscillations for detection of flaws in different materials have developed into classical investigations based on measurements that take into account the entire range of important influencing factors. Today, ultrasonic testing, supported by greatly advanced instrument technologies, yields reproducible test results within narrow tolerances [1].

## 2. Immersion Testing

The immersion ultrasonic testing is one of the ultrasonic testing techniques used for the quality control of welds. The space between search unit and work piece must be relatively large and be filled completely with a liquid coupling medium (e.g. water). Immersion technique is characterized by the fact that coupling operations are optimal. Covering the shortest dead zones, this technique is optimal for local and remote resolving. Although any liquid may be used, water is preferred for most applications. The distance between search unit and test specimen must be selected in such a way that the echoes are clearly separated from the work piece by the repetitions of the surface echo. For a complete examination, either search unit or work piece must be moved while the selected sound direction is kept constant [2].

### 2.1 Straight- beam Examination

The ultrasonic device, therefore, must be adjusted in such a way that at least a first back-wall echo is emitted from the specimen before the second entrance echo appears. In the case, if the second entrance echo appeared before the first back-wall echo from the work piece, a sure interpretation of the echo indication would be not possible. The length of the “water delay block” should be chosen therefore such that the above mentioned conditions are fulfilled. The adjustment range is always selected for the material that is being tested. Therefore, the value of the water delay block is related to the ratio of the sound velocity:

$$s_w = \frac{c_w}{c_{st}} s_{st} \quad (1)$$

where:  $s_w$  – water delay block,

$c_w$  – sound velocity for water (1480 m/s),

$c_{st}$  - sound velocity for material (steel) (5920 m/s),

$s_{st}$  - sound path in the material (distance between first and the second entrance echo in the material) [2].

### 2.2 Angle Beam Examination

For angle beam examinations during immersion testing, probes are mounted in a holder (manipulator), considering a predetermined incident angle to the work piece surface. To calculate the angle of incidence, one must know the sound velocities of the appropriate kinds of waves in the water as well as in the specimen. The computation law for the setting angle  $\alpha_w$  of the immersion probes is as follows:

$$\sin(\alpha_w) = \frac{c_w}{c_{st,transversal}} \sin(\beta_{st}) \quad (2)$$

where:  $c_w$  – sound velocity for water;

$c_{st,transversal}$  – speed of sound for material for transverse waves (3165 m/s);

$\beta_{st}$  – intromission angle in material (steel)

Since the sound velocity in water is highly temperature-dependent, the water temperature must be kept almost constant during testing to avoid changes in the sound angle  $\beta$  [2].

### 2.3 Focusing Immersion Probes

To achieve an even better resolution and a higher sound pressure at predetermined depth ranges, one frequently applies a focusing immersion probe. Focusing is achieved mainly by means of a set of spherical lenses placed in front of the transducer. Another possibility is to use curved transducers. There are two kinds of focusing immersion probes, i.e. point-focusing and line-focusing ones. For line-focusing probes –here a focus has a form of a long elongated ellipse- the scanning field is broader in the work piece so, that the specimen with a broader scanning trace could be examined. The long-range flaws, for example cracks, which are oriented in the direction of the long axis of the sound beam profile, are proved optimally with the line-focusing probes. With point-focusing probes the highest sensitivity within a small, circular range of the bundle could be achieved [2].

## 3. Examinations of Defects in EUROFER with Immersion Testing

Three types of welding seams (i.e. seams obtained by diffusion welding, electron-beam welding, TIG welding) with differently arranged artificial flaws were examined. The simulated flaws consisted of longitudinal holes and cross holes with diameters ranging from 0.2 mm to 1.0 mm and tungsten wires of 0.2 mm to 1.0 mm in diameter. The experiments were performed applying straight- and angle beam examination methods activating longitudinal and transverse waves by varying the resolutions of the sensors. Eventually, the DAC (Distance Amplitude Correction) curves for flaw sizes between 0.2 mm and 0.1 mm in diameter were obtained on the basis of the transverse wave examinations.

The specimens were tested using the KC 200 immersion testing facility developed by the GE Inspection Technologies (Fig. 1). The facility KC-200 includes a water tank, a multi-channel ultrasonic device USIP 40 on PC basis and K-Scan software for an efficient data acquisition with different scan size and a representation of the test results as A, B, or C-scan. The tank is provided with motorized X, Y- and Z-axes and a water filter system. In addition, the system is equipped with a rotating unit. Transducers (and cable connections) for immersion testing are waterproof.

### 3.1 Diffusion Welding

Straight-beam examinations of the diffusion-welded samples were performed using a 25 MHz point-focused sensor (type IAP-25.3.1) for detection of flaws of different geometries and diameters (cross- and longitudinal holes).



Fig. 1: Immersion testing facility KC-200

Therefore, three identical welded specimen of constant bottom thickness (4 mm) and variable upper part thicknesses (19 mm, 8 mm, 4 mm) and a sample of equal thickness of upper and bottom parts (5 mm) were chosen for the experiments. Amplifications of 88 dB and 92 dB were chosen during testing.

In the first specimen (thickness of upper part = 19 mm), all holes were invisible in spite of an amplification of 92 dB and an adjusted focusing depth (focus = 4 mm in the material and still 15 mm away from the welding seam). Holes contours can be detected only with the screen moving till the back wall echo.

In the case of the second sample (thickness of upper part = 8 mm), the focusing depth was changed from about 1.5 mm to about 4 mm in the material at an amplification of 92 dB. With a focus adjustment of about 5 mm relative to the welding area (3 mm in the material), the longitudinal holes  $\varnothing$  0.5 mm (L = 4 mm) and  $\varnothing$  0.4 mm (L = 4 mm) and also the cross hole  $\varnothing$  0.3mm (L = 2 mm) could be well identified and measured (Fig.2). However, the hole that was 0.3 mm in diameter and no more than 2 mm deep remained invisible due to technical reasons.

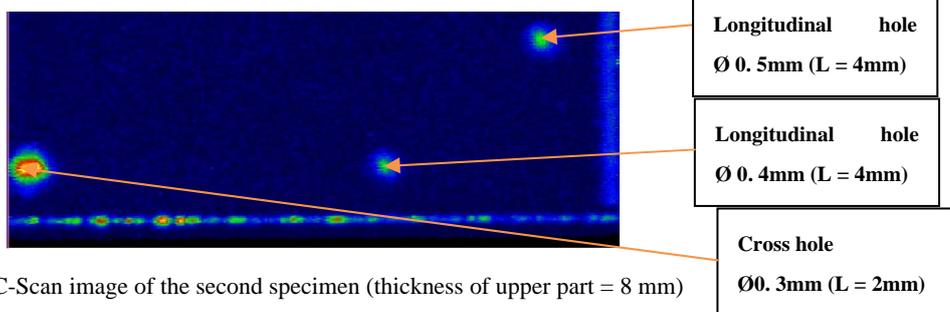


Fig. 2: C-Scan image of the second specimen (thickness of upper part = 8 mm)

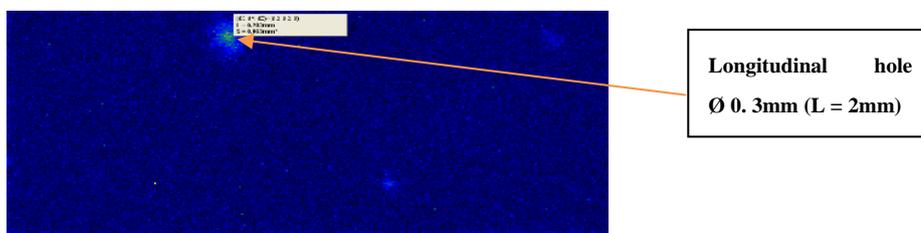


Fig. 3: C-Scan image of the third specimen with the focus about 4 mm to the drilling ground

In the third sample (thickness of upper part = 4 mm), the longitudinal holes  $\varnothing$  0.5 mm,  $\varnothing$  0.4 mm and the cross hole  $\varnothing$  0.3 mm were very clear and correctly measurable at an amplification of 88 dB and with focusing on the surface. The longitudinal bore  $\varnothing$  0.3 mm (L = 2 mm),

however, was still invisible at a focus adjustment like that. When a higher amplification (92 dB) was selected and the focus of the sensor was inserted deeper into the sample (about 2 mm into the material, 2 mm away from the welding seam), the result was positive and even a small flaw was detected (Fig.3).

In addition to the holes, two transverse slots with widths of 0.2 mm and 0.1 mm were inserted in a 10 mm thick sample (5 mm - upper section and 5 mm - lower part) on the lower plate to simulate cracks at an amplification of 88 dB. The C-scan reveals that a strong dispersion is emitted from these slots (Fig. 4).

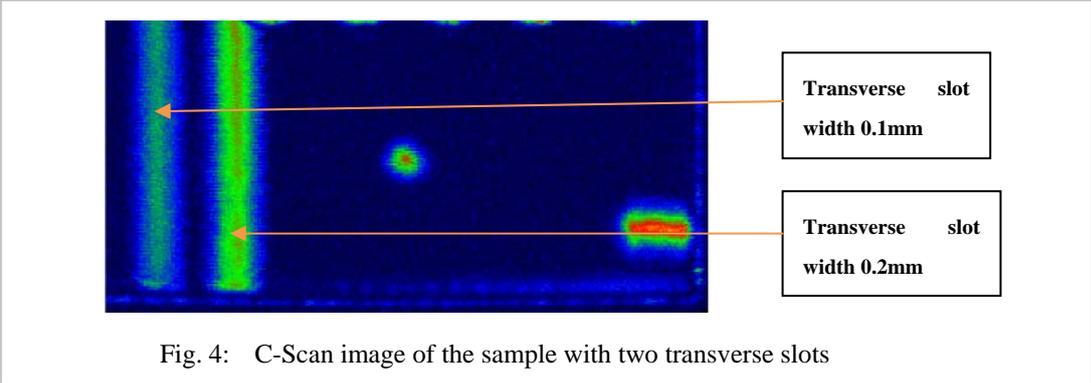


Fig. 4: C-Scan image of the sample with two transverse slots

### 3.2 Electron-Beam Welding

Electron-beam welded specimen were provided with butt-welded seams, L- and T-shaped seams using two EUROFER plates with different kinds of artificial flaws such as holes and tungsten wires (1.0 mm in diameter) inserted within and outside of the welding range. All tests were performed using a point-focused 15 MHz transducer (type ISS).

In the case of the butt-welded sample, the tungsten wire (0.5 mm in diameter and 10 mm in length) was directly introduced into the welding seam and two longitudinal holes ( $\varnothing$  0.55 mm, 6 mm deep and  $\varnothing$  0.2 mm, 2mm deep) had been drilled in the material. Applying different adjustment (the straight- and angle beam examinations) and using the amplification of 82 dB, the artificial flaws could be identified (Fig. 5).

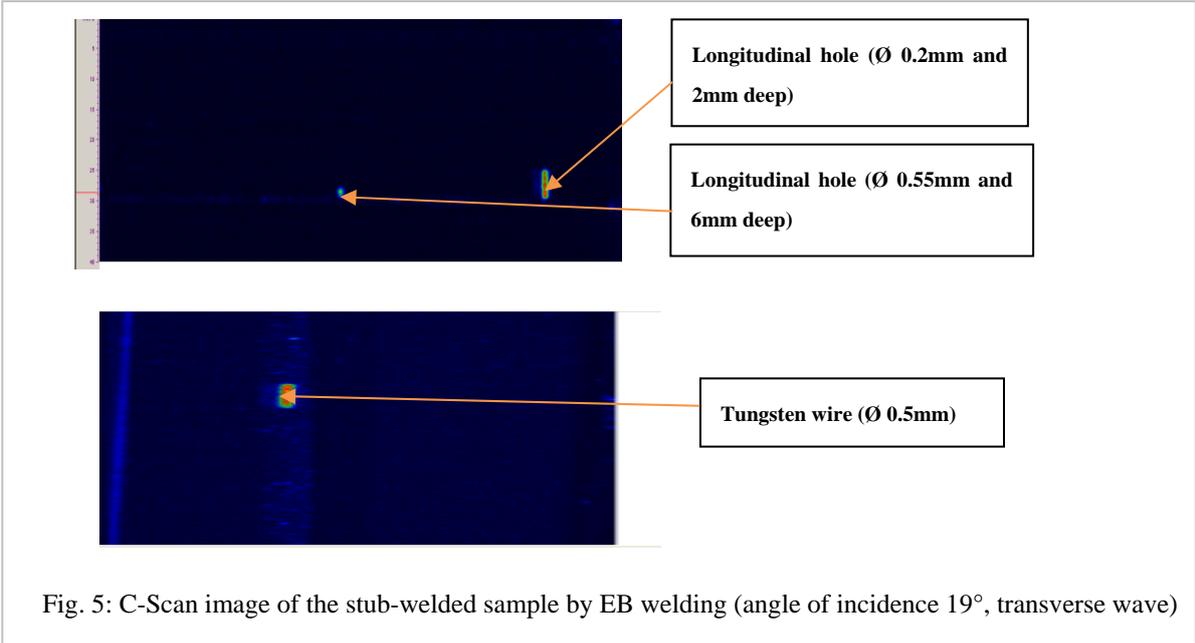


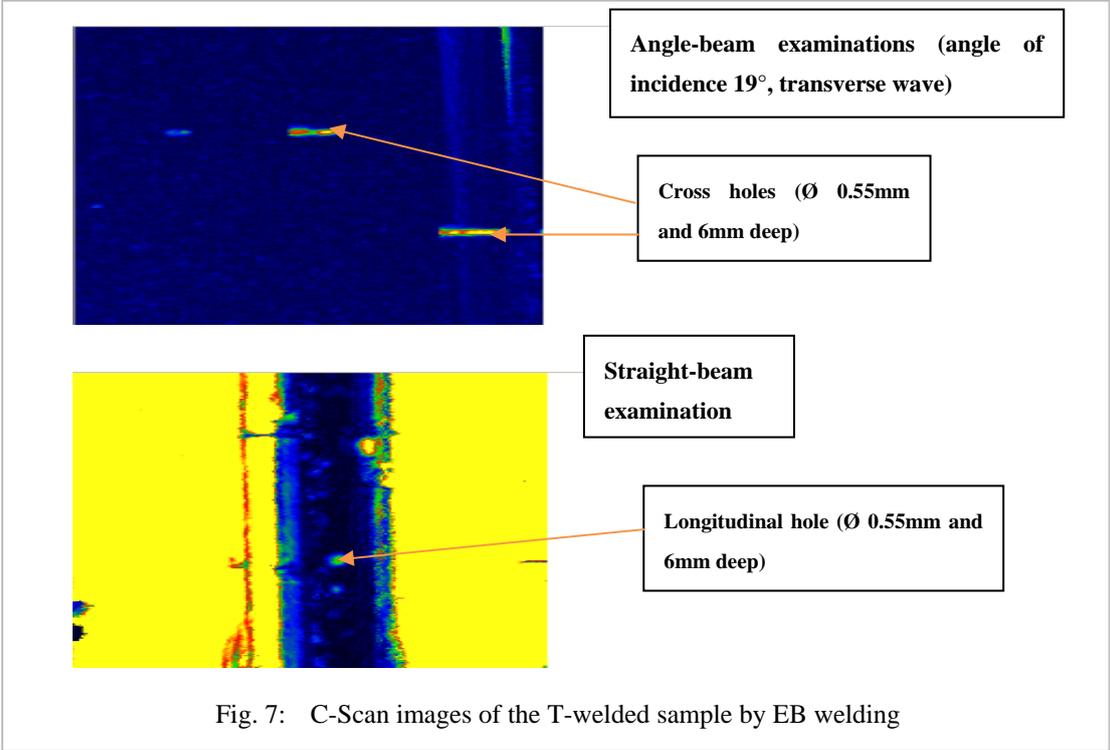
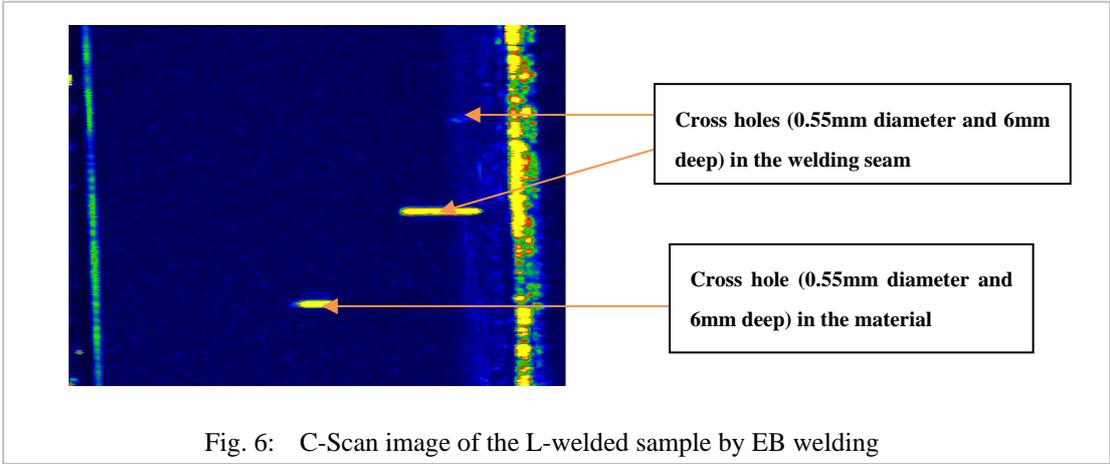
Fig. 5: C-Scan image of the stub-welded sample by EB welding (angle of incidence 19°, transverse wave)

The L-welded sample having three cross holes (0.55 mm in diameter and 6 mm deep) in and outside of the welding seam. The holes (one - in the material and two - within the welding range) were drilled in different cut layers with intervals of 20 mm.

Choosing a setting angle of  $\alpha_w = 19^\circ$  with transverse waves and changing the positioning of the specimen, all three artificially inserted holes could be rather well identified at an amplification of 80 – 82 dB (Fig. 6).

The analysis of the T-welded sample was performed both with straight-beam and angle beam adjustment. The specimen has a longitudinal hole ( $\varnothing$  0.55 mm and 6 mm deep), from the welding area down through the base and three cross holes ( $\varnothing$  0.55 mm and 6 mm deep).

Using an amplification of 82 dB while applying different settings (angle of incidence changes and wavelength varies) and changing the direction of the scan, all registered flaws could be detected rather clearly (Fig. 7).



### 3.3 TIG Welding

The quality of the TIG-welded seams corresponded to that of the electron-beam welded ones, i.e. samples were butt-welded, L-welded and T-welded and were made from two EUROFER plates with artificially introduced flaws in and outside of the welding. Once again, a point-focused 15MHz encoder (type ISS) was used for ultrasonic testing.

The specimens tested first were butt-welded samples with differently arranged artificial flaws. In essence, the artificially introduced flaws consisted of cross holes ( $\varnothing$  0.55 mm,  $\varnothing$  0.5 mm and  $\varnothing$  0.2 mm) as well as of tungsten wires whose diameter was in the range of 0.2 mm to 1.0 mm. During ultrasound testing, the specimens were examined both with straight-beam and angle beam adjustments. The longitudinal (in the straight-beam examinations) and transverse (in the angle beam examinations) waves were energized. Using different angle settings of the sensor and varying the wavelength, all artificially inserted flaws could be rather well identified at an amplification of 80 – 85 dB (Fig. 8, 9).

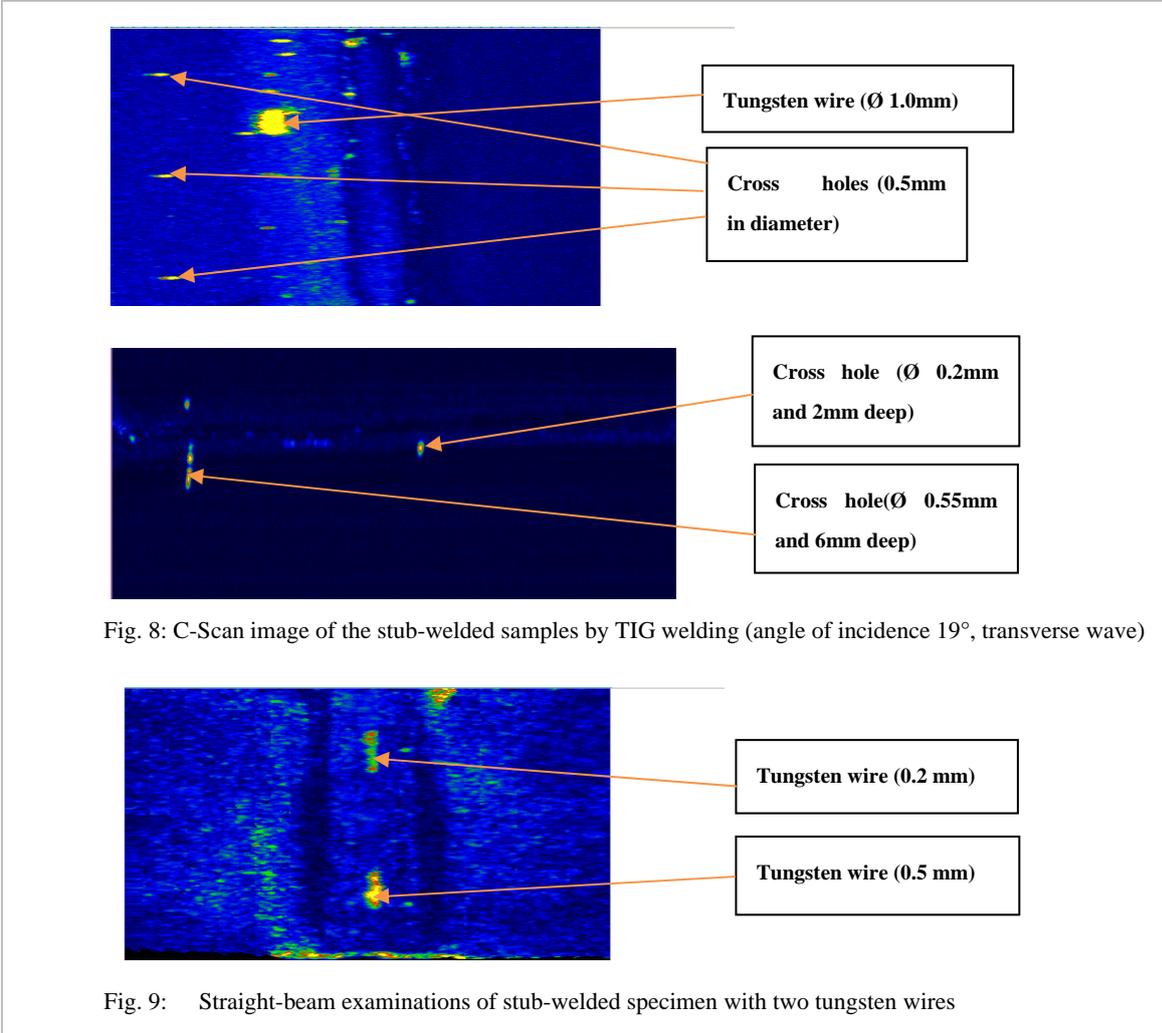
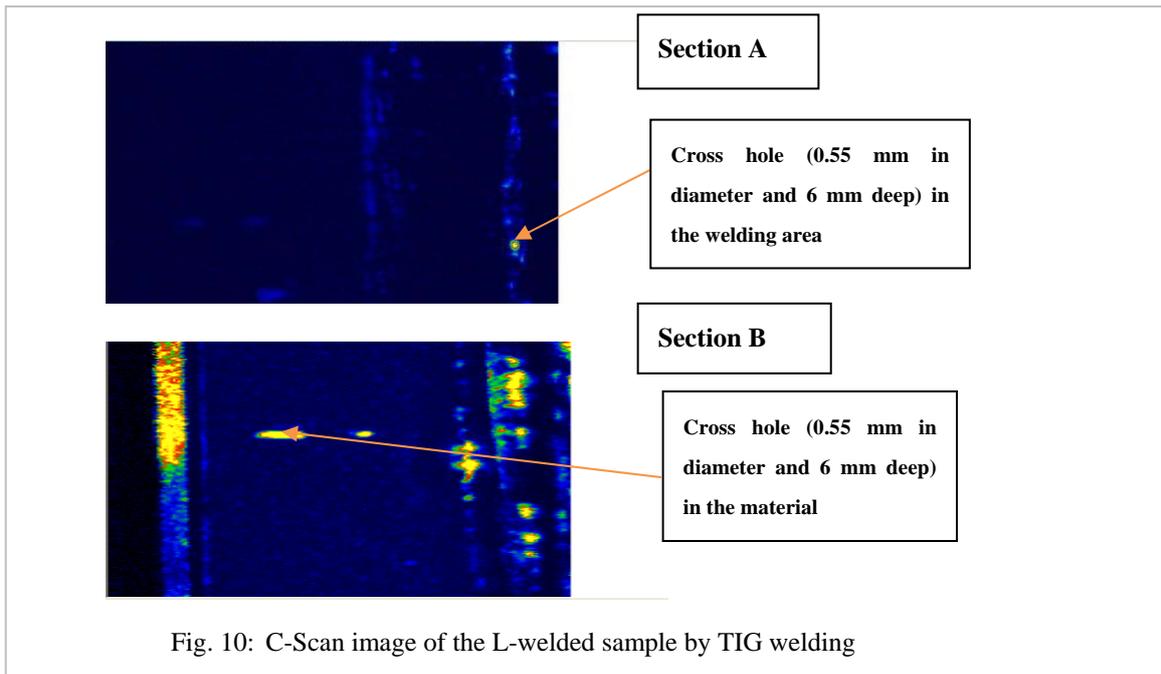


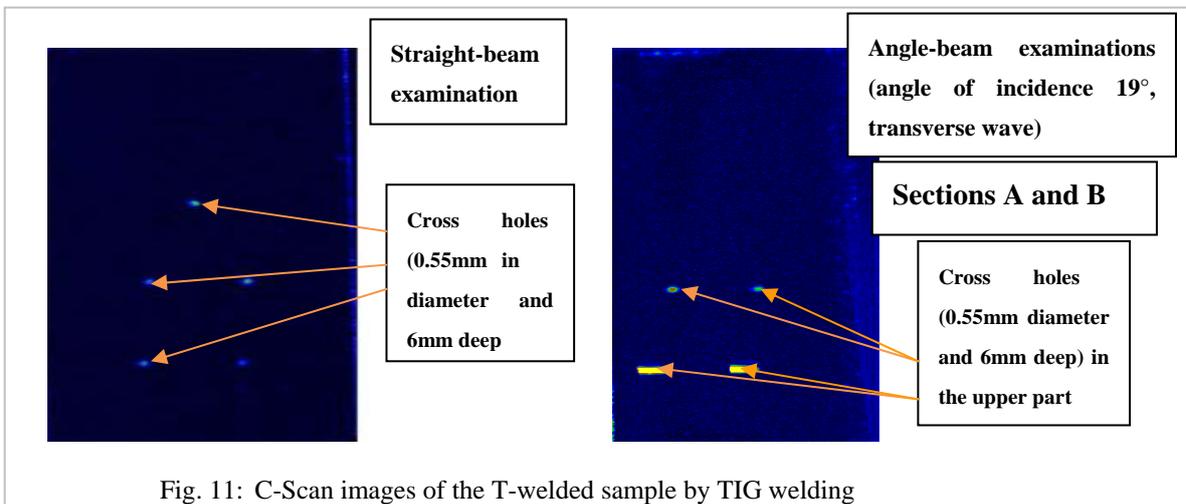
Fig. 8: C-Scan image of the stub-welded samples by TIG welding (angle of incidence 19°, transverse wave)

Fig. 9: Straight-beam examinations of stub-welded specimen with two tungsten wires

For identification of the artificially introduced flaws (holes - 0.55 mm in diameter and 6 mm deep) in an L-welded sample the setting for transverse waves was used. All of the flaws prepared were detected by changing the direction of the scan and varying the position of the test object (Fig. 10). Amplification was at 82 dB.



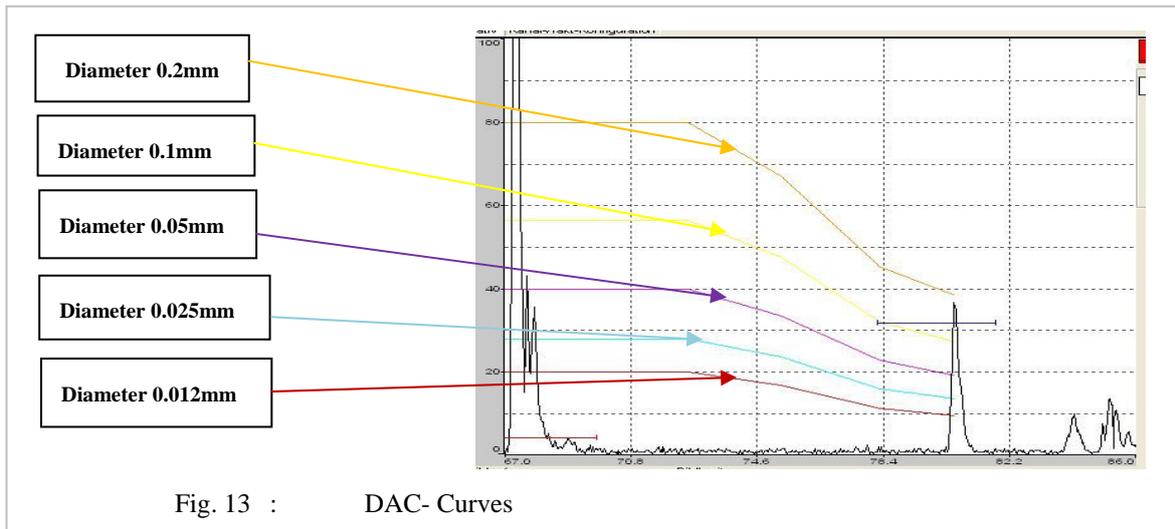
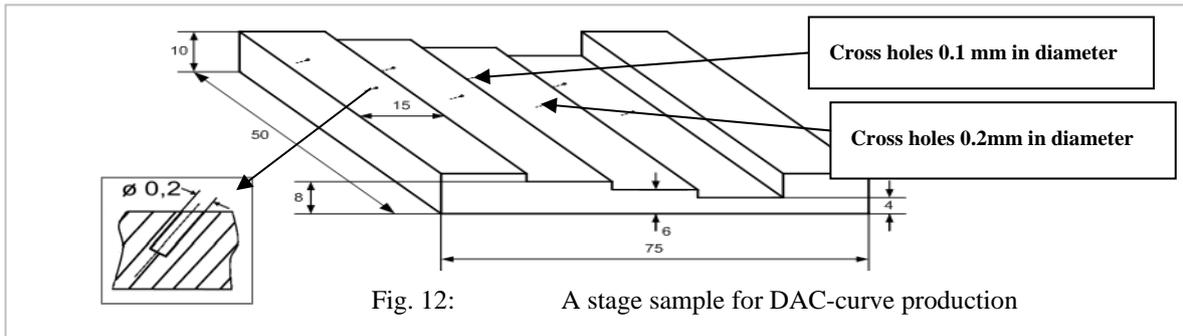
During ultrasound testing, a T-welded specimen with differently arranged cross holes (0.55 mm in diameter and 6mm deep) was examined both with straight-beam and angle beam adjustments. The longitudinal (in the straight-beam examinations) and transverse (in the angle beam examinations) waves were energized. By changing the sensor positioning and varying the positions of the sample at amplification in the range of 80 – 82 dB, also these flaws were detected (Fig. 11).



### 3.4 DAC (Distance Amplitude Correction) - Curve Production

In our case was used a stage sample with inserted cross holes 0.2 mm and 0.1 mm in diameter as a reference block for DAC curve production (Fig. 12).

The DAC curve was generated for the 15 MHz sensor (type ISS) and for the transverse wave settings (angle of incidence 19°, transversal wave length). The amplification in the experiment was in the range of 70 – 72 dB. The DAC curves for the cross holes 0.2 mm in diameter are shown in Fig. 13.



#### 4. Conclusions

Application of the automated ultrasonic immersion technique enabled the examinations of EUROFER parts for blanket components of future fusion reactors including welding seams of the different types (diffusion welding, electron-beam welding and TIG-welding). In the context of this work the minimally visible flaw sizes have been determined in diverse types of welding joints for different welded samples:

- In a diffusion-welded samples flaws of 0.1 mm in size can be detected provided that the distance from the wave entrance surface is of about 5 mm;
- In TIG-welded and in electron-beam welded the flaws of 0.2 mm in size can be found.

DAC (Distance Amplitude Correction) curves were generated for flaws sized 0.2 mm and 0.1 mm in diameter. By using the decrease in amplification and generating several DAC curves (a multi-DAC curve); also very small flaws (down to e.g., 0.025 mm and 0.012 mm) might be evaluated.

#### 5. References

[1] D. Volker, Die Ultraschall- Prüfung (1999)  
 [2] M. Berke, U. Hoppenkamps, Krautkrämer Training System, Tauchtechnikprüfung (2001)