QUALITY EVALUATIONS OF THE FUEL BUNDLE WELDS AND BRAZED JOINTS BY ACOUSTIC MICROSCOPY

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ABSTRACT

For more than 20 years, the quality control of the end-cap, end-plates welds and of the brazed appendage joints is made by destructive methods (metallographic examinations or mechanical tests) on specimens sampled from production.

Having a very limited statistics, these destructive methods are useful only to indicate "trends" of the production quality, not for detecting infrequent single defect events.

It is recognized that nondestructive examination techniques are required to achieve sufficient evidence of the production quality, at a statistically significant sampling rate.

For this reason, the INR-Ultraacoustics R&D Lab has develop a family of equipments for high resolution ultrasonic imaging, at performances close to the Acoustic Microscopy domain.

The paper make a presentation of the examination methods and of the experimental results obtained on characteristic welds and brazed joints samples. Detailed off-line evaluations of the C-scan and B-scan ultrasonic images are made and comparative analyses with metallography are performed. Also, in the case of end-cap welds, numerical stress analysis are made, in order to establish the influence of flaws on the weld strength.

1. INTRODUCTION

The nuclear fuel bundles of CANDU type consist of a number of zircaloy-4 clad fuel elements spot-welded, at each end, to an end plate (figure 1).

Main mechanisms of in-reactor defects of the fuel bundles are related especially to the fuel elements closure welds (end-cap welds) and end-plate welds. These are: opening-up of incomplete welds and fatigue growth of the cracks initiated in the weld **heat-affected zone (HAZ)** [11].

In order to reduce the in-reactor failure probability, it is necessary to have a minimum number of defects in the final manufacturing stage.

For this, it is recognized that nondestructive examination methods are required to achieve sufficient "visibility" of the production quality, at a statistically significant sampling rate [12].

Ultrasonic examination is of a particular interest because it allow the volumetric characterization of the structural integrity of the welded and brazed zones, inclusively HAZ; high resolutions can be obtained with the new high-frequency imaging techniques [10].

On the other hand, being a relatively high-speed nondestructive method,the ultrasonic examination can be applied for a statistically significant quality evaluation.

2. MICROSTRUCTURE CHARACTERIZATION OF THE FUEL BUNDLE WELDS

Being electric resistance welds, the end-cap and the end-plate welds are essentially solid-state bonding with a sandwich-like macrostructure [3]. There are three distinct zones around the welded regions (figure 2, for the case of the end-cap weld [13]):

a) base metal (zone 1, equiaxed grains);

b) recristallized zone (zone 2, slightly elongated grains parallel with the weld-line);

c) dynamically recristallized zone (zone 3, fine-grained, containing persistent limits due to precipitation of the alloying elements, especially Sn).

These zones have not only different microstructure, but also they have different mechanical and acousto-elastic properties [2]. However, they have sufficient high ultrasonic transparence and lower microstructure noise for a good signal to noise ratio, even to 50MHz.

3. EXAMINATION METHOD AND EQUIPMENTS

The nondestructive examination of the fuel bundle welds and brazed joints is based on the automatic scanning of the weld and brazed zones with a very high focused ultrasonic beam. To perform this, high resolution computer controlled mechanical scanning devices were developed. Synchronous with the scanning of the investigated spatial domain, automatic acquisition of the ultrasonic amplitude and time-of-flight data are performed. In this way, ultrasonic C-Scan and B-Scan images of the welds volume are obtained [1].

The examination is made in immersion, using high-frequency/high-damped transducers, with beam incidence on the cap surface (fig.4), for the end-cap welds, on the external plate surface in the case of the end-plates welds (fig.6), and on the bearing pad or inter-element spacer surface (fig.5) in the case of brazed joints examination.

The block-diagram of the MICROSCAN equipments for Acoustic Microscopy investigations by C-scan and B-scan methods, is presented in fig.3.

For obtaining a good in-depth resolution, the ultrasonic signals are broad-band amplified with a bandwidth close to the frequency response range of the transducer.

For obtaining a good lateral resolution, the flaw signal are separately amplified in a narrow-band tuned on a frequency selected in the high-frequency region of the spectral response of the transducer.

In figure 9, it is shown the frequency response of a high-resolution transducer, used in our investigations (IAP-FM 25.3.1/KRAUTKRAMER).

For this transducer, which are 0.3mm beam diameter, the minimum size of the detectable flaw was determined by extrapolation of the amplitude response obtained for axial holes with different diameter values (Φ_1=0.14mm, Φ_2=0.2mm, and Φ_3=0.3mm, fig.8). The results are presented in figure 10, for two different cases:

a) At 83dB gain (the current value for end-cap examination). In this case, the noise is lower than the 8% amplitude threshold of the USIP12 flaw detector, and the corresponding minimum size of the detectable defect is around 80μm diameter.

b) At 92dB gain, which correspond to 100% full scale amplitude of the axial hole with Φ_2=0.2mm diameter. In this case, the maximum noise level is 14% of the amplitude scale, and the corresponding minimum size of the detectable defect is around 75μm diameter. This is a physical limit of the system, for the specified transducer. It is important to note that, because of the complex welds geometry, both position and width of the flaw gates are variable during the scanning process.

4. EXPERIMENTAL RESULTS

End-cap welds examination

Three types of flaws are typical for the end-cap examination, as it results from our investigations:

(1) Incomplete welds along the weld line (fig.13, right).

(2) Inclusions in the HAZ (fig.13, left).

(3) Cracks at the reentrant corner (fig.11 and 12).

The incomplete welds is the most common defect type and it is also provided and currently evaluated by the metallographical procedures. The inclusion-type flaw and the flaws in the reentrant corner zone are not usually the object of metalographic examination procedures.

However, these type of flaws are very significant for the structural integrity of the end-cap weld, as it is discussed in the reference [4] and is, also, demonstrated by our calculations of stress distributions (chapter 5).

End-plate welds examinations

The most frequent type of flaw encountered in our investigations are 2-dimensional border defects, associated with transversal aria reduction of the weld zone. Some times, in these distorted welds, isolated internal flaw are present, as it can be seen in fig.15.

Generally, the welds from the external circle of the plate-end are symmetric and with a minimum of 3.5mm in diameter (fig.14). The defect welds are most often present on the internal circles of the plate-end.

Brazed joints

Porosity in the brazing zirconium beryllium alloy are the most common defect (fig.16).

Frequently, porosity is associated with high thickness of the brazing layer. If the distance between the isolated pores are lower than the wavelength, the ultrasonic echo signal is of multipole type.

5. CALCULATIONS OF THE STRESS DISTRIBUTION AROUND DEFECTS IN THE END-CAP WELDS

The estimation of stress and strain state in the end-cap region is an important part of general threshold to analyse components with high defect probability of CANDU fuel bundle [5,6]. The analyse method developed in present work is of a large applicability, in what it concern the geometric and physical particularities and the operation conditions on which fuel elements are subjected. Also, it is important to sustain the end-cap weld acceptance criteria and to describe the fuel defect mechanisms.

The methods consist in linking a computer code for simulation of the CANDU fuel type, together with a code using finite element method for thermo-mechanical analysis.

First, we use the ROFEM 1.0 [14] code, which is able to predict the in-pile thermal and mechanical behavior of fuel rods, to compute pellet deformations in normal conditions with several burnup histories. The geometrical parameters are varied in the design limits. To point out the worst case (e.g., conditions for which the radially and axially pellet displacements are greatest) we use response surface method (RSM) [7].

Finally, we made a statistical analysis concentrated on contribution to pellet deformation, sheath thickness, gap, shanfren and depth of pellet dish and also a combination of those.

The detailed local thermo-mechanical analysis in order to estimate stress and strain state and work density is performed by means of two-dimensional axisymmetric finite element method with the TEPSAC code [8].

The TEPSAC code performs general thermal and mechanical analyses with the finite element method. The analysed structures are planar and axisymmetric and can be meshed in triangle or quadrilateral elements. The type of analyses solved by TEPSAC are steady-state or transient thermal analyses, elasto-plastic and creep analyses or any other combination of those.

The code uses the von - Misses formulation to define the yield surface, and the Prandtl -Reuss flow rule to define the incremental plastic strains.

The code can be used to analyse more than one material with different physical properties. The mechanical properties as Young modulus, Poisson coefficient, plastic modulus, yielding stress can be expressed as functions of temperatures and strain rate.

The accuracy of the TEPSAC code has been verified against a wide range of analytical solutions [9].

In the mechanical analyse, we use a small region that contains the end-cap, weld line and a part of sheath. It is made by around 450 elements, 40 of them being along the weld.

Material properties are temperature dependent and, also we consider the metallurgical state of Zircaloy-4. Yielding stress of melt material from weld region is 20% less than the value of sheath material (figure 2).

Applied loads are: pellet displacements obtained from ROFEM 1.0 code, coolant pressure and temperature distribution. We suppose that the pellets interact in radial direction with the sheath and in axial direction with the end-cap.

To estimate the influence of defects on the end-cap weld strength, we perform calculation with different positions of a flaw in weld line, from outside to inside of the element. The radial size of flaw is 12% from sheath thickness.

In figure 17, we present the effective stress and strain and work density at the end-cap /sheath interface as a function of flaw position. For comparison, we have shown the computed value in case of no-flaw, with dashed line.

The results indicate that a flaw positioned at 60 - 80% ST have a significant influence on stress and strain state of weld and over 110% ST the influence of void position become insignificant.

6. CONCLUSIONS

The nondestructive examination of the CANDU fuel bundle welds and brazed joints is possible by high-frequency ultrasonic techniques.

The INR-Ultraacoustics R&D Laboratory has developed the MICROSCAN-02 equipment for ultrasonic examination of the end-plates welds and brazed joints and the MICROSCAN-03 equipment for ultrasonic examination of the end-cap welds. The depth and lateral resolution of these equipments are close to the Acoustic Microscopy domain.

In fact, an effective resolution of 0.05mm can be obtained for x50 magnification factor. Thus, the ultrasonic C-Scan and B-Scan images can shown microstructure details at a scale comparable with the usual metallography.

On the other hand, the ultrasonic method has the advantage to be a high-speed nondestructive method which provide a volumetric characterization of structural integrity of welds and brazed joints.

Powerful calculus methods are developed for analysis of the stress and strain distribution around the flaws.

ACKNOWLEDGMENTS

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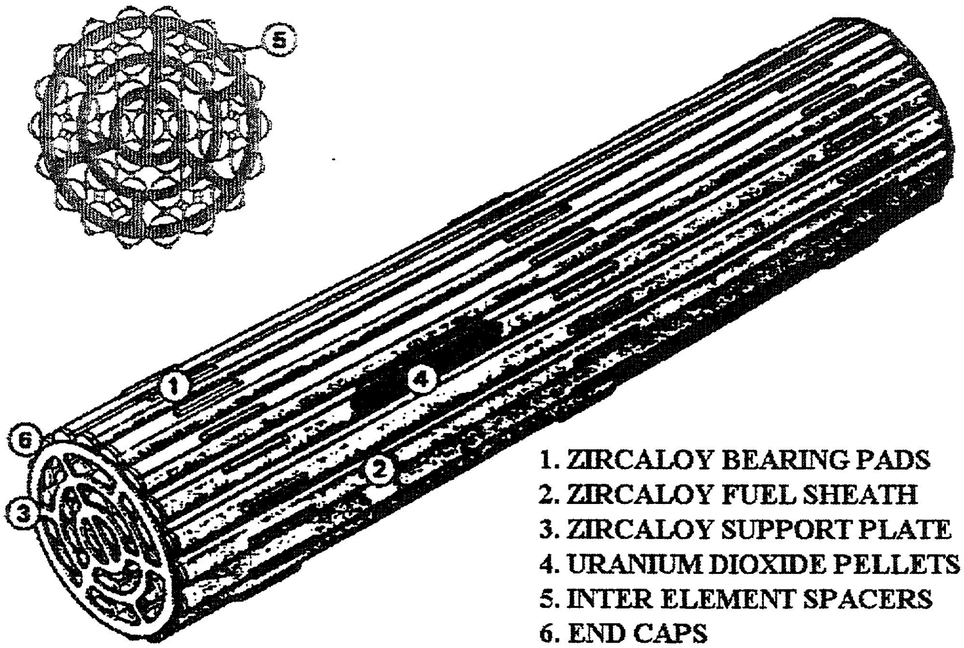


Fig. 1. CANDU 37 nuclear fuel bundle

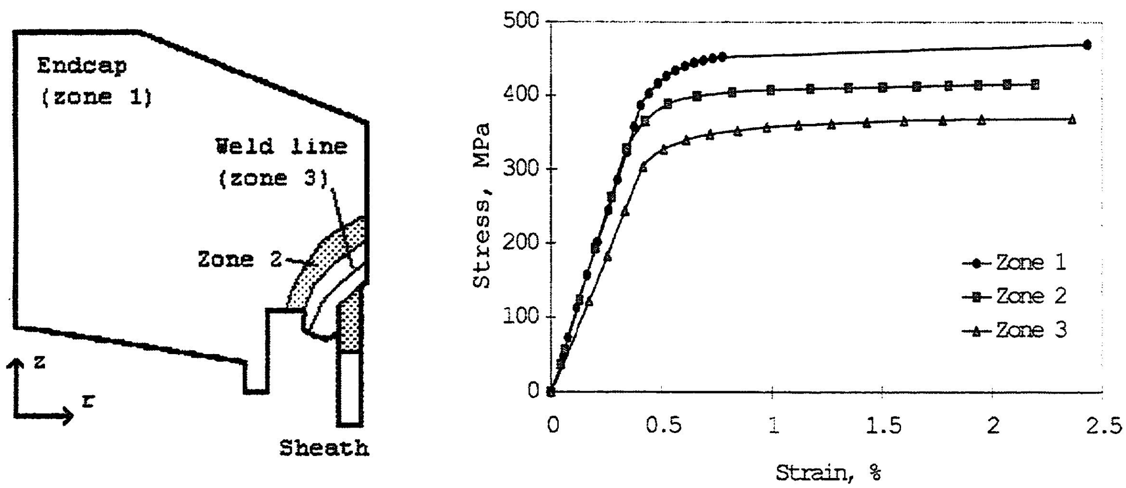


Fig. 2. The local properties zones around a typical end-cap weld

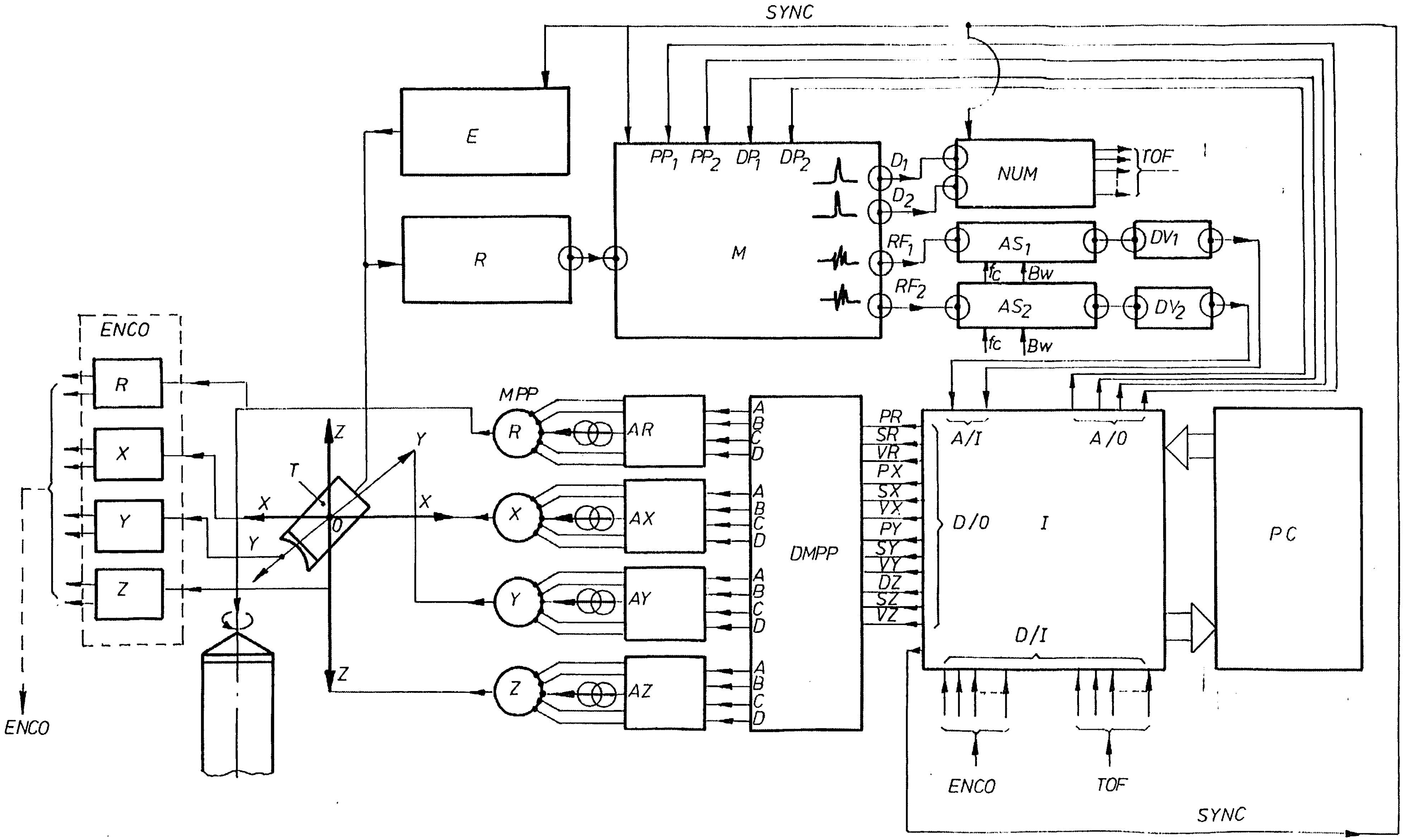


Fig.3. BLOK-DIAGRAM OF THE ACOUSTIC MIKROSCOPY EQUIPMENTS

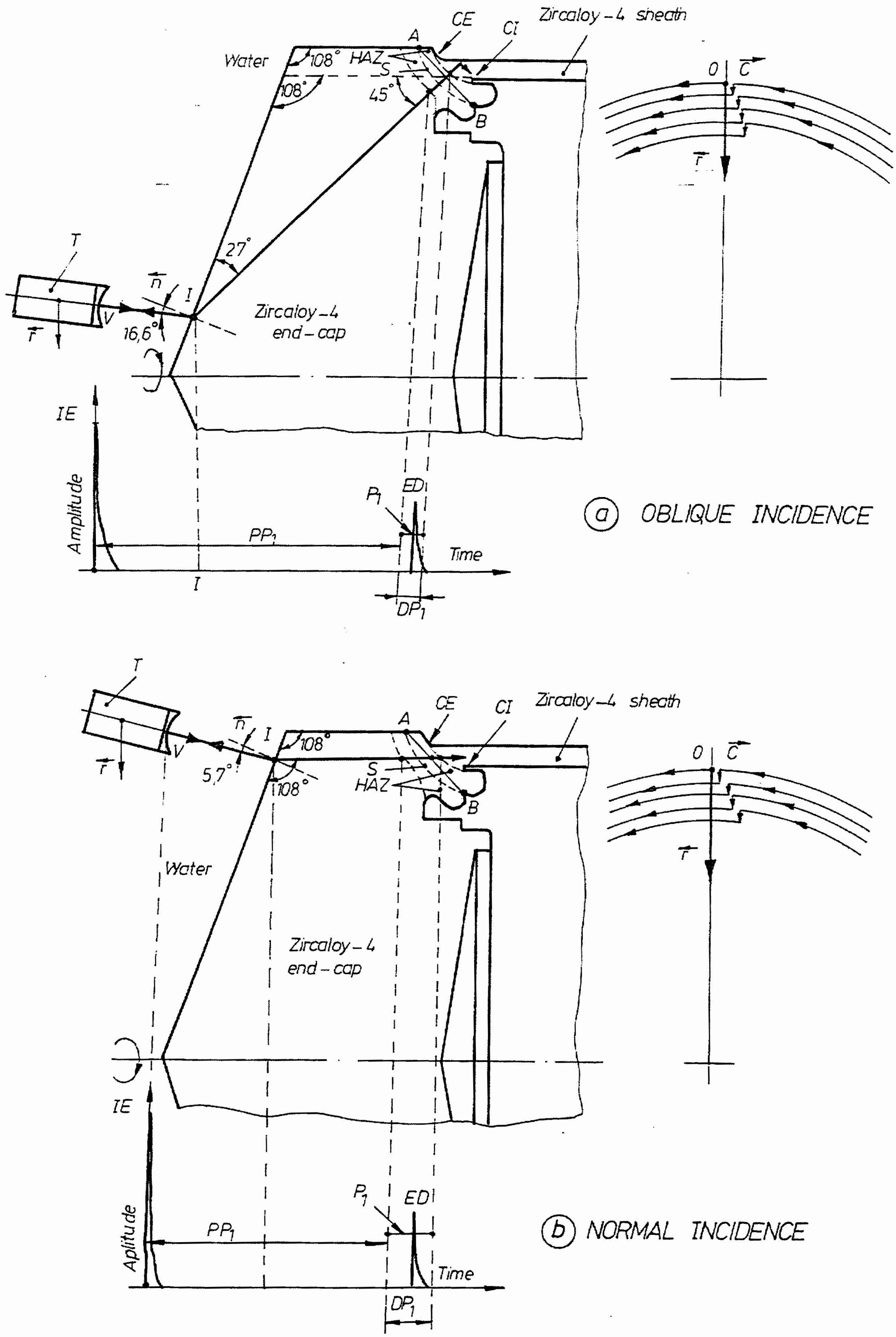
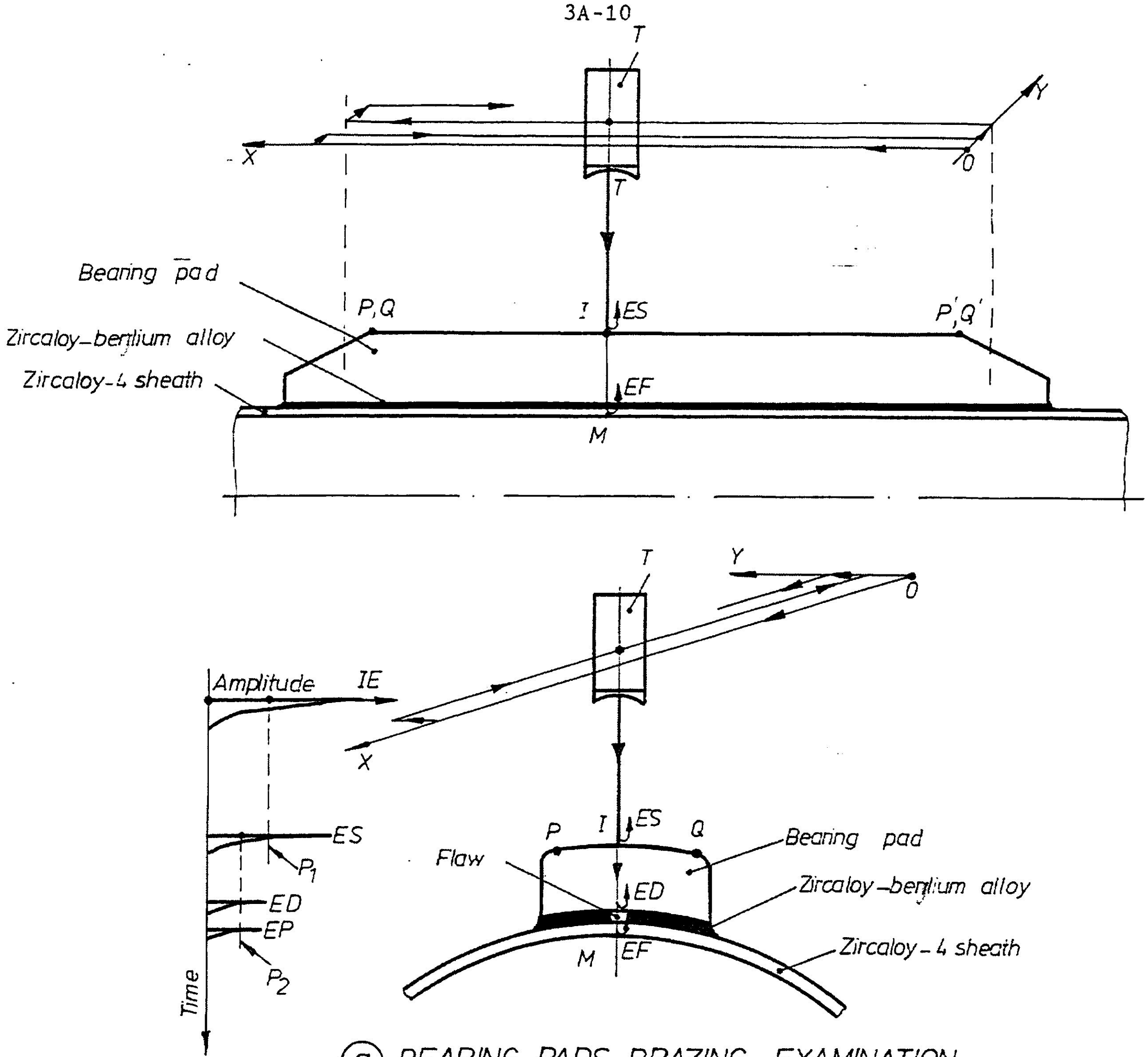
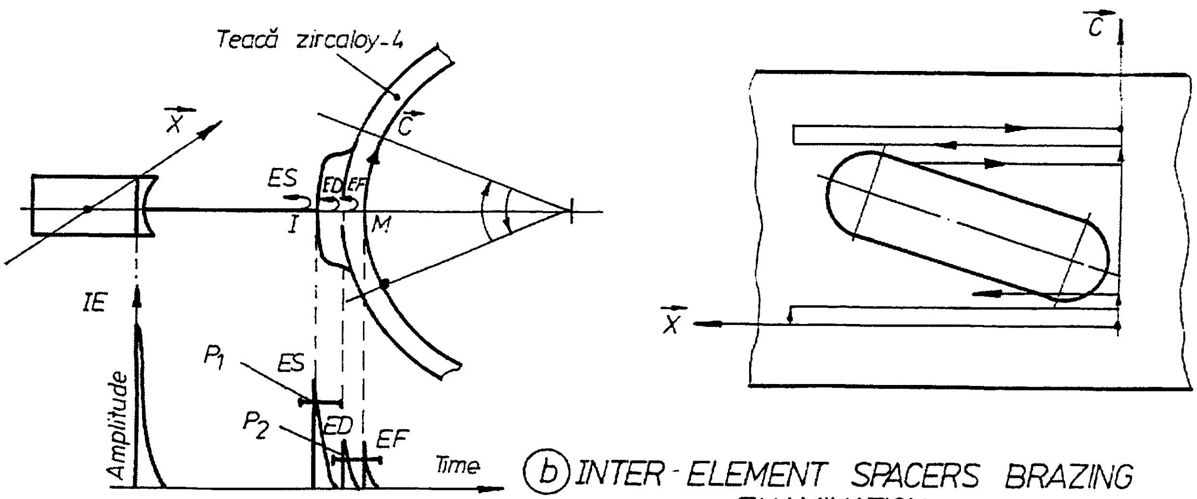


Fig. 4. SCANNING GEOMETRIES FOR THE END-CAP WELD EXAMINATION

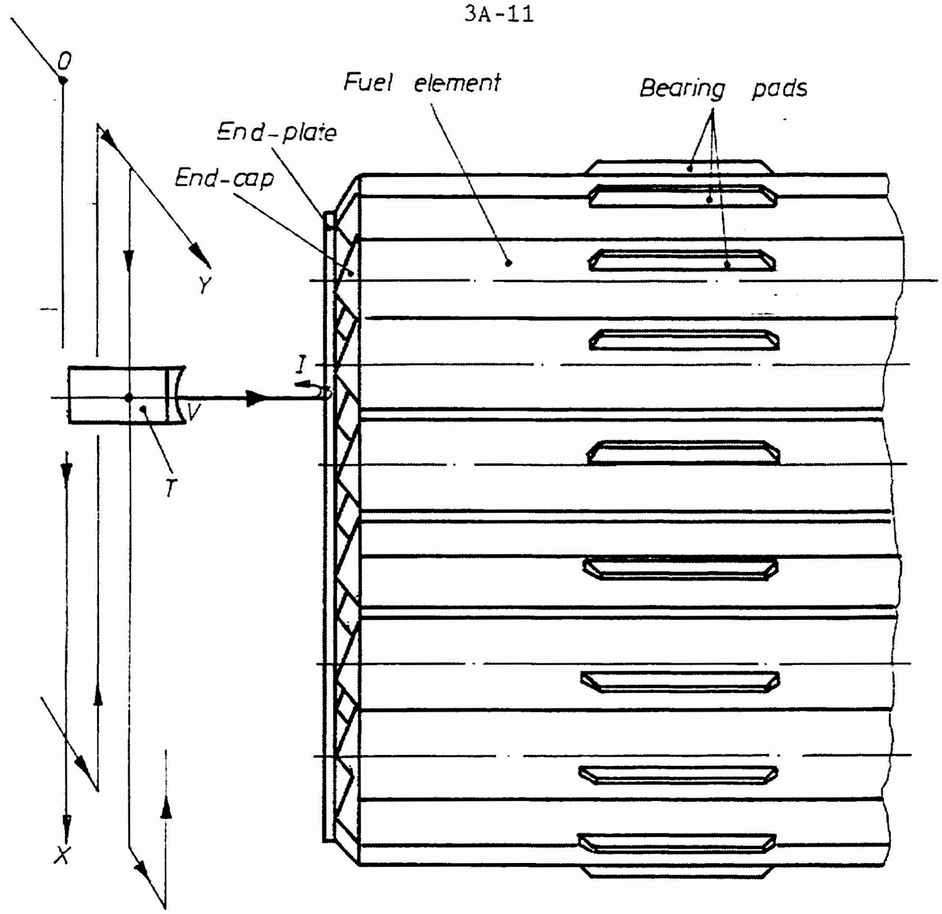


(a) BEARING PADS BRAZING EXAMINATION



(b) INTER-ELEMENT SPACERS BRAZING EXAMINATION

Fig. 5. SCANNING GEOMETRIES FOR THE BRAZED JOINTS EXAMINATION.



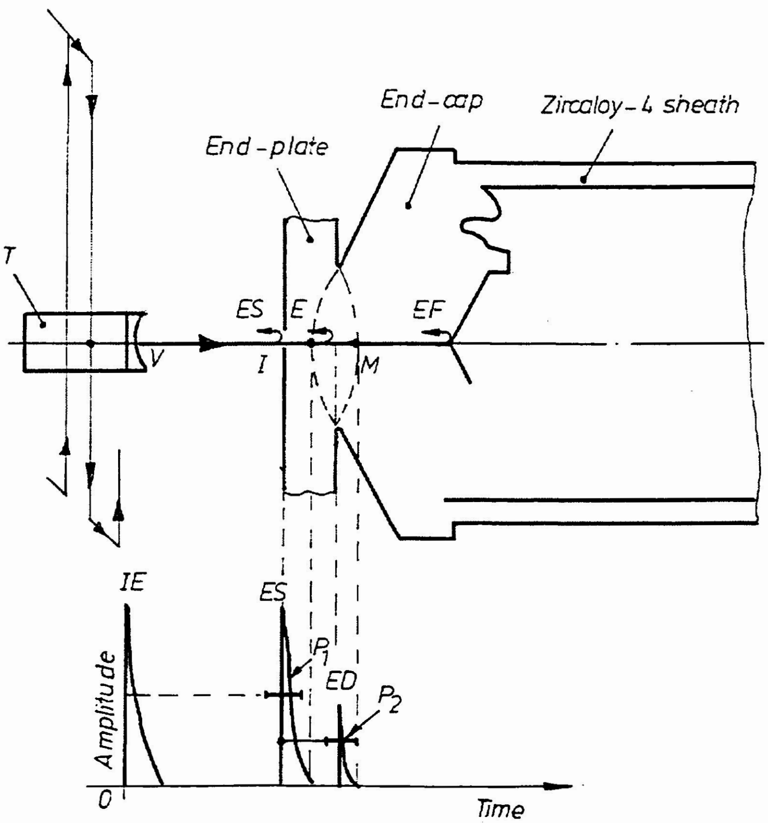


Fig. 6 SCANNING GEOMETRY FOR THE END PLATE WELDS EXAMINATION

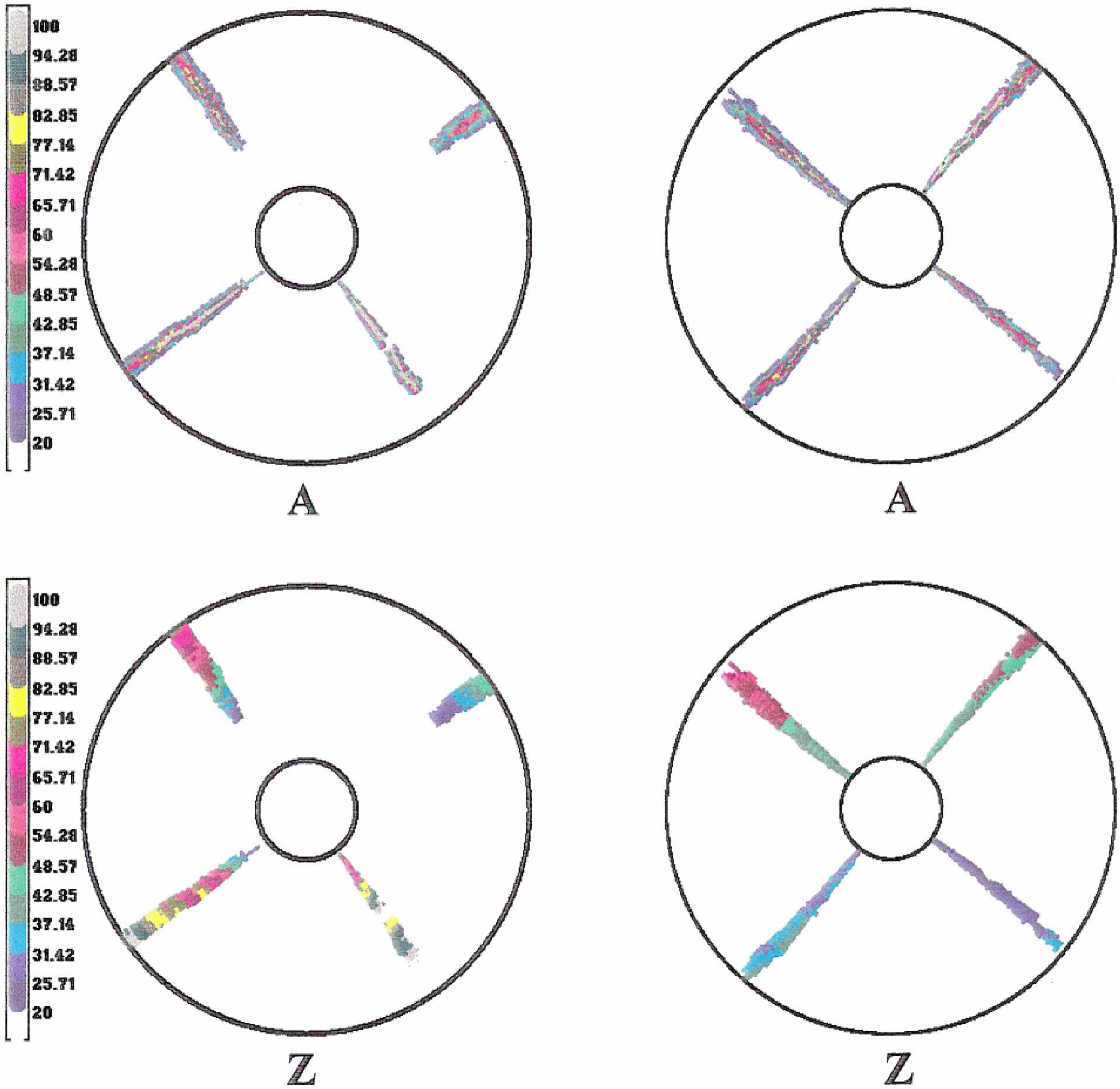
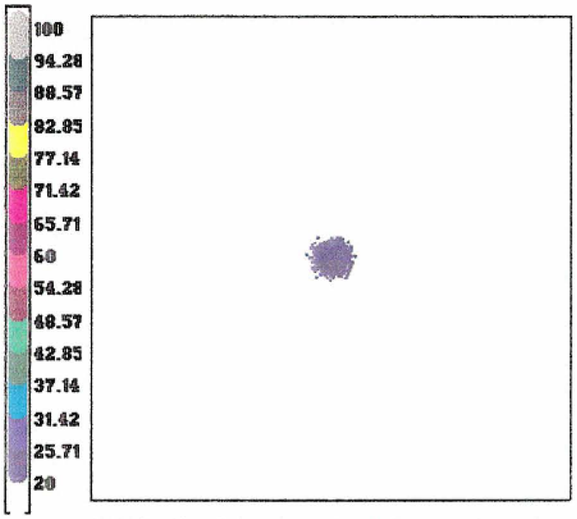


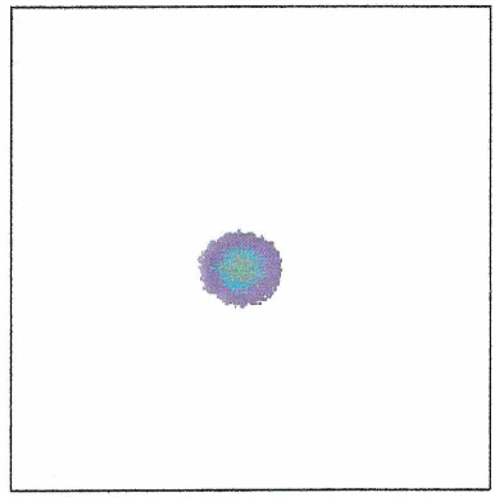
Fig. 7.Ultrasonic amplitude(A) and time-of-flight(Z) images of the reference samples for calibration at normal incidence (left) and oblique incidence (right) in the case of the end-cap welds examination

PARAMETERS

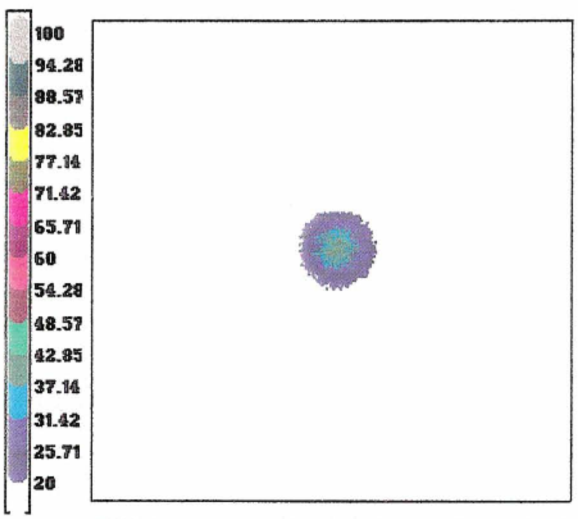
Sample Code	**: DTNC1 (four radial holes of 0.5mm diameter)**	**DTIC1 (four holes of 0.5mm diameter, inclined to 45° in the radial-axial plane)**
Transducer	**: IAP.FM 25.3.1 / KRAUTKRAMER**	**IAP.FM 25.3.1 / KRAUTKRAMER**
Gain	**: 88 dB**	**88dB**
Detection Threshold	**: 20%**	**20%**
Scanned Zone	**: 0--360°/Circumferential Resolution = 0.07mm 0--1.2mm/Radial Resolution = 0.05mm**	**0--360°/Circumferential Resolution = 0.07mm 2--4.4mm/Radial Resolution = 0.05mm**



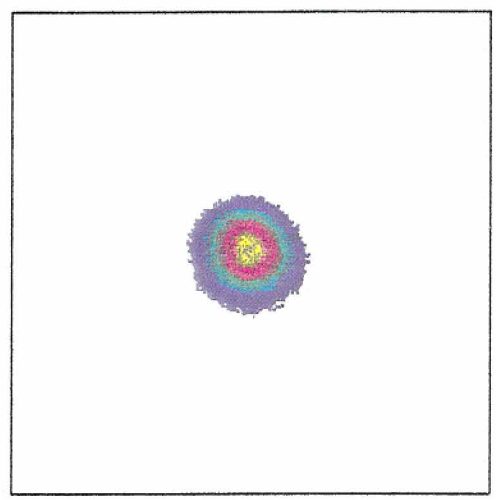
Sample: DTS-6(axial hole of 0.14mm diameter)



Sample: DTS-5(axial hole of 0.2mm diameter)



Sample: DTS-4(axial hole of 0.3mm diameter)



Sample: DTS-3(axial hole of 0.4mm diameter)

Fig. 8. Ultrasonic amplitude images of the minimum defect size reference samples at normal incidence

PARAMETERS

Transducer	**: IAP.FM 25.3.1 / KRAUTKRAMER**
Gain	**: 63 dB**
Detection Threshold	**: 20%**
Scanned Zone	**: Rectangular 2x2mm^2 / Resolution = 0.005mm**

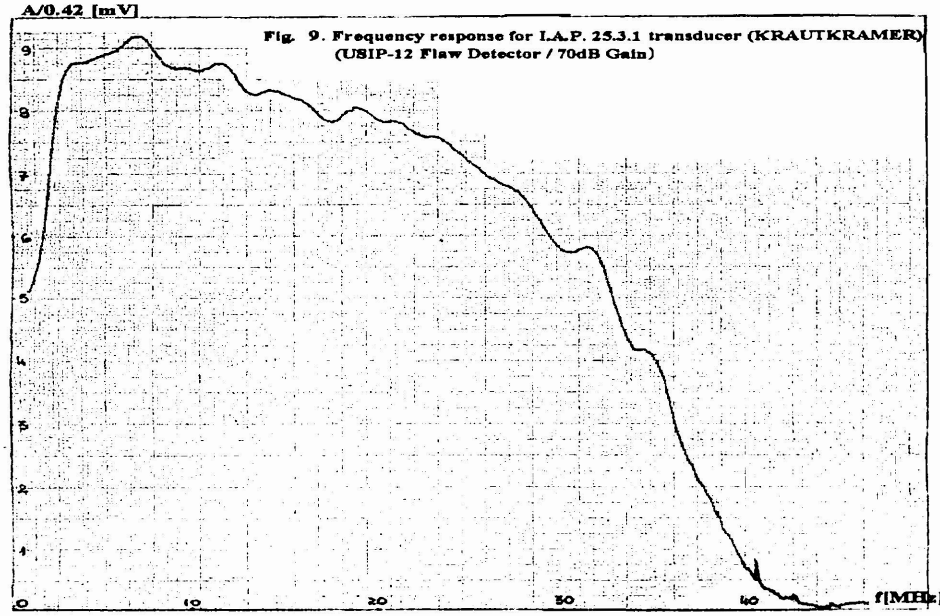
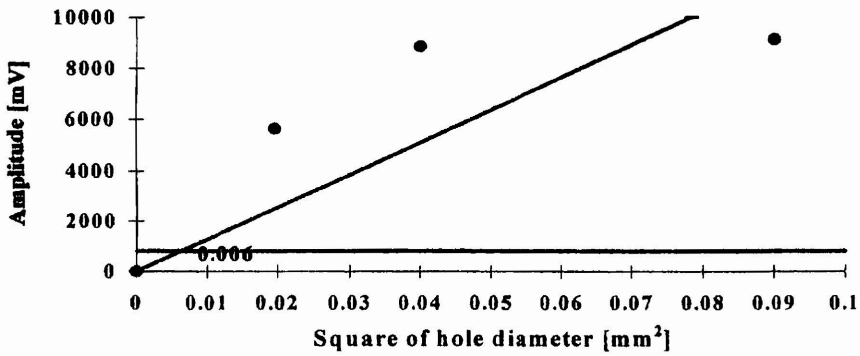
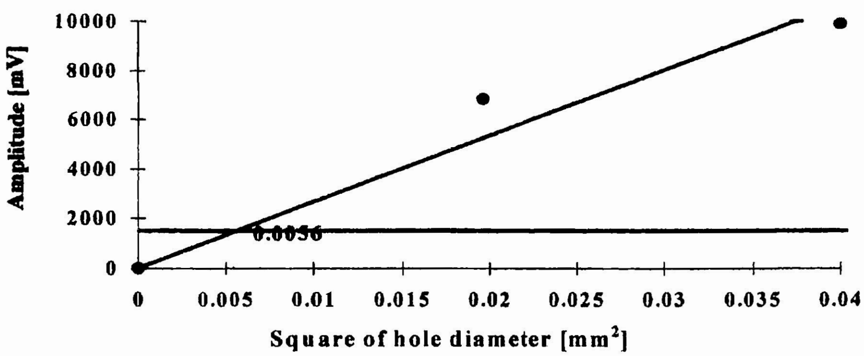


Fig. 9. Frequency response for I.A.P. 25.3.1 transducer (KRAUTKRAMER) (USIP-12 Flaw Detector / 70dB Gain)



a)



b)

Fig. 10. Evaluation of minimum detectable defect size:

a) on calibration conditions for current examination of end-cap welds (gain 83dB)

b) on 92dB gain value, corresponding to 100% full scale amplitude for the axial hole with 0.2mm diameter

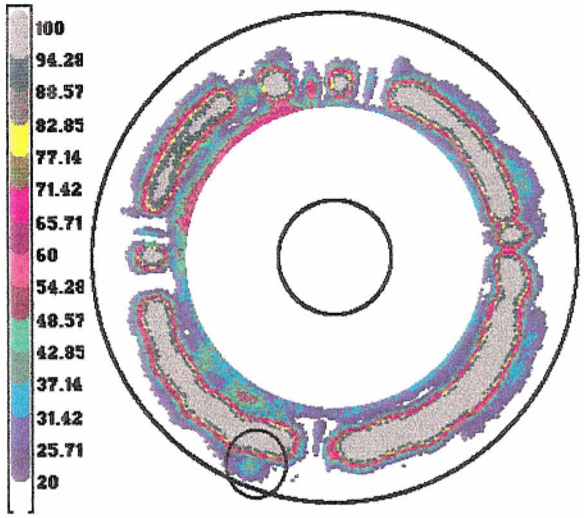


Fig. 11. Ultrasonic amplitude image for sample DT18 at normal incidence. In the encircled zone it can be seen the image of the reentrant corner flaw from fig. 12.

PARAMETERS

Sample Code	**: DT18**
Transducer	**: IAP.FM 25.3.1 / KRAUTKRAMER**
Gain	**: 83 dB**
Detection Threshold	**: 20%**
Scanned Zone	**: 0--360°/Circumferential Resolution = 0.1mm**
	0--1mm/Radial Resolution = 0.025mm

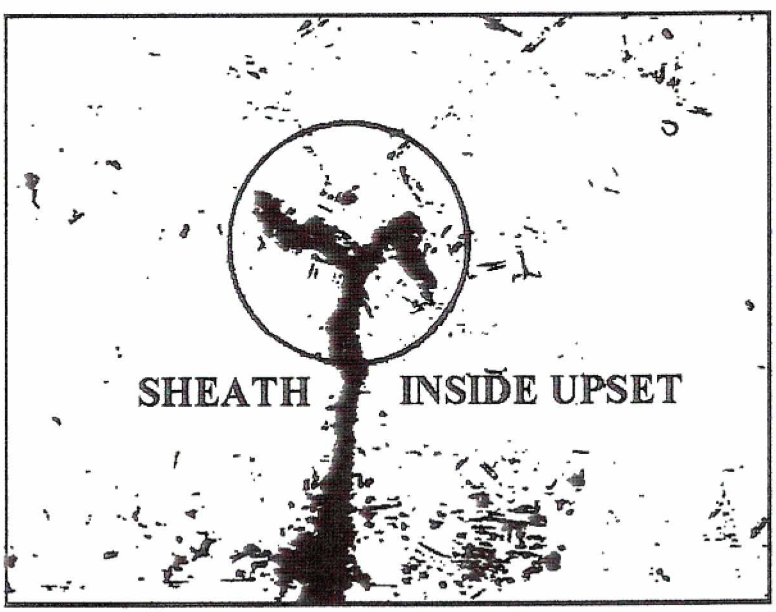
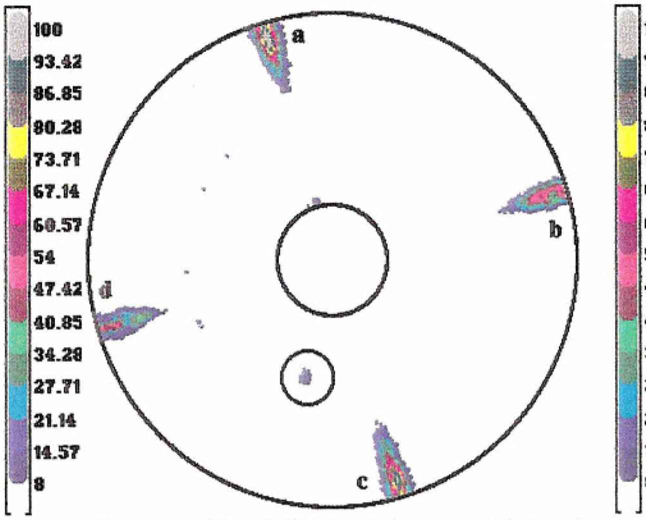
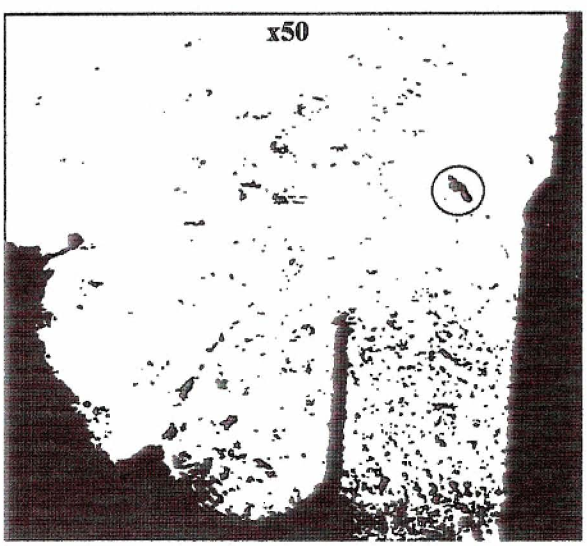
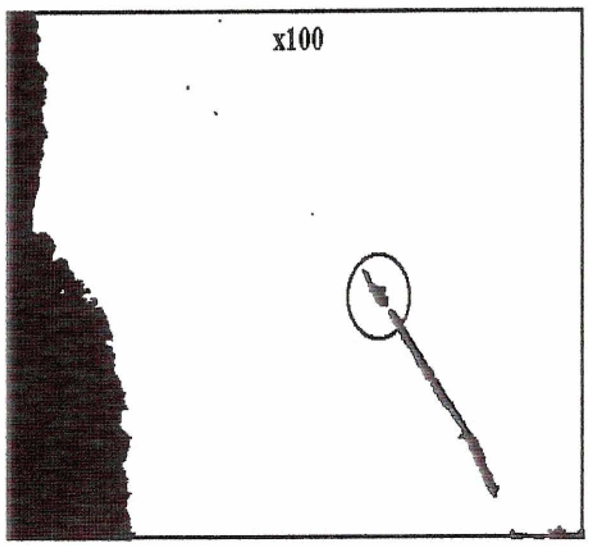


Fig. 12. Metallographic aspect (x500) of an reentrant corner crack.



a, b, c, d are artificial flaws (0.5mm radial holes)





Sample: ESN

Sample: DOP1

Fig. 13. Ultrasonic amplitude images and metallographic aspects for an inclusion type flaw in the HAZ (left) and for weld line type flaws (right).

PARAMETERS

Transducer	**: IAP.FM 25.3.1 / KRAUTKRAMER**
Gain	**: 83 dB**
Detection Threshold	**: 20%**
Scanned Zone	**: 0--360°/Circumferential Resolution = 0.07mm**
	2--2.4mm/Radial Resolution = 0.05mm

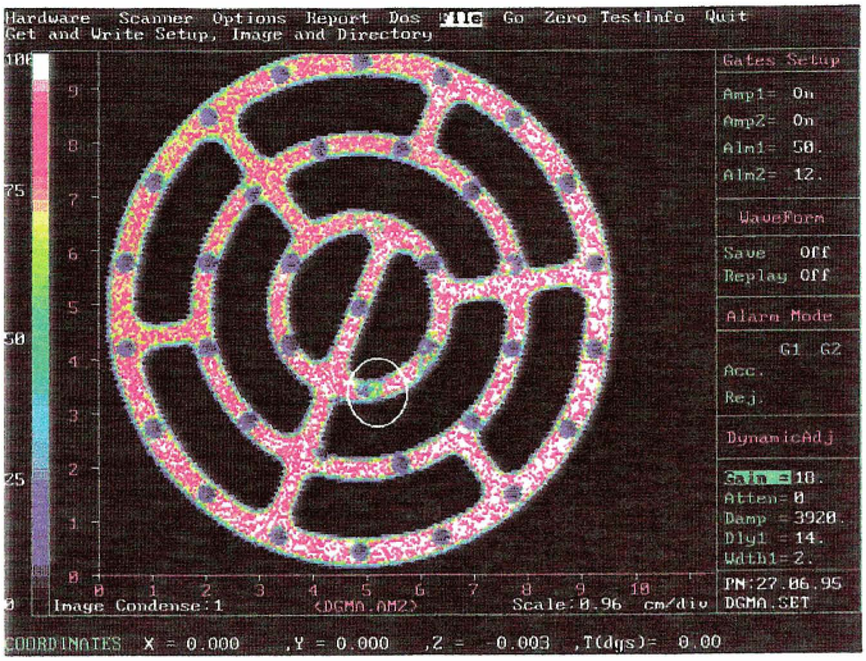


Fig. 14. Ultrasonic <u>amplitude</u> image of a welded end-plate.

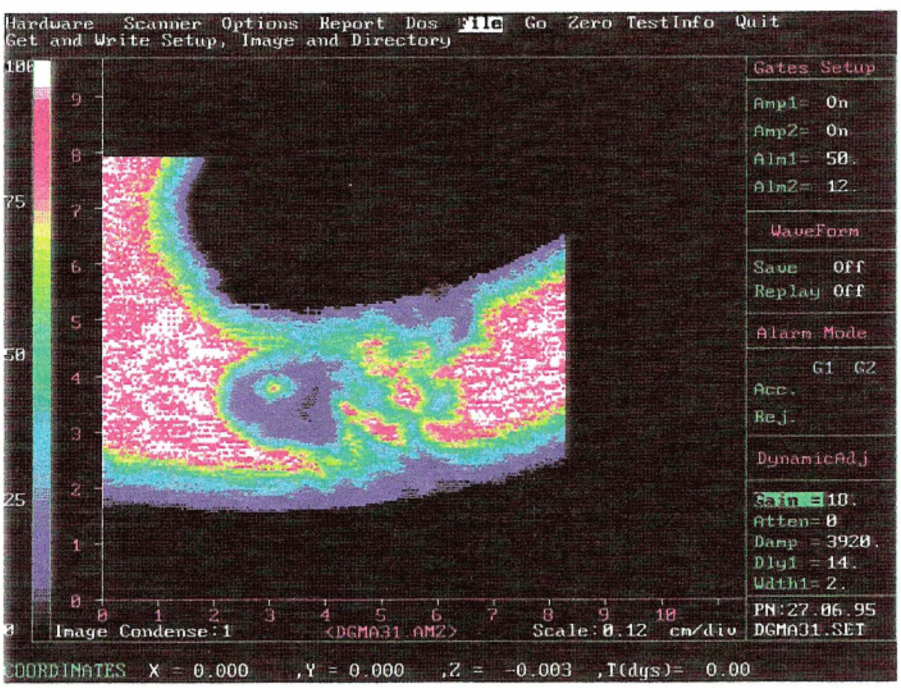
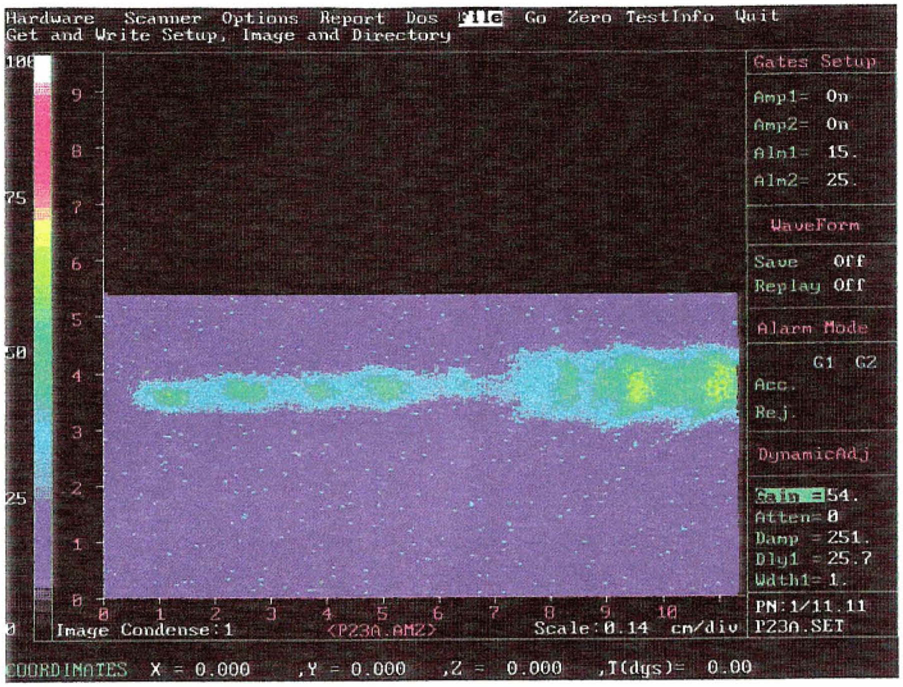
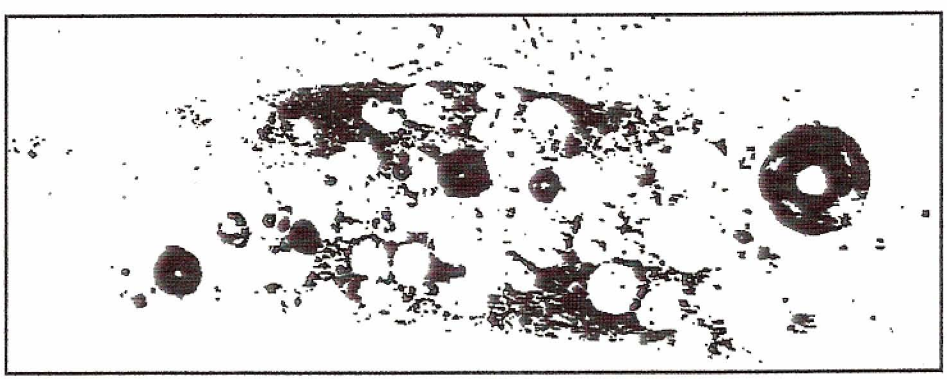


Fig. 15. Ultrasonic <u>amplitude</u> image of the defect weld encircled in fig. 14.



a)



b)

Fig. 16. Ultrasonic <u>amplitude</u> image (a) and <u>metallographic</u> aspect x250 (b) of porosity defects in a bearing pad brazing

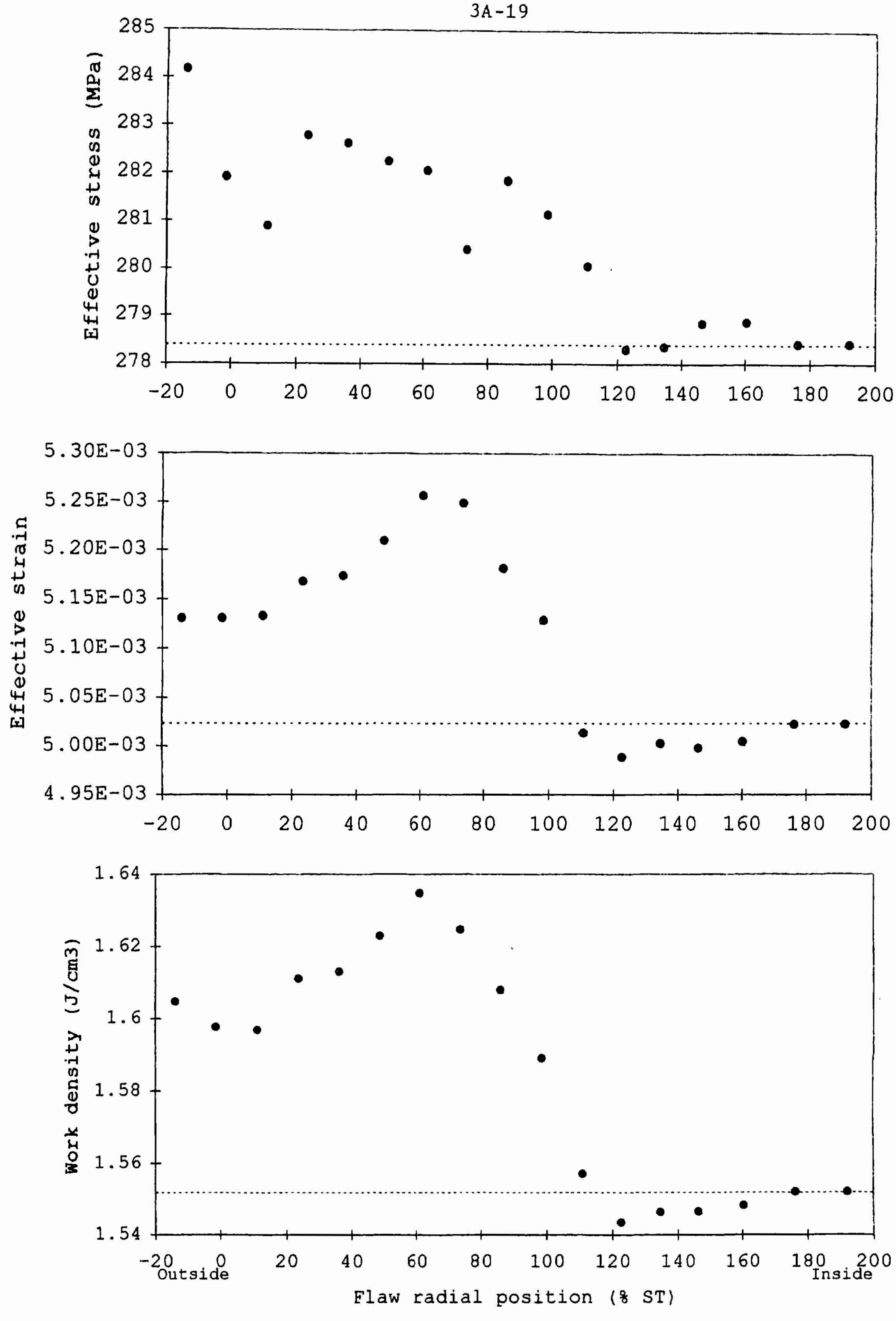


Fig. 17. Evolution of effective stress, strain and work density as a function of radial positon of flaw