ALOK-IMAGING AND -RECONSTRUCTION OF SURFACE DEFECTS ON HEAVY PLATES WITH E.M.A.-RAYLEIGH WAVE TRANSDUCERS

Hans Rieder and Hans-Jürgen Salzburger

Fraunhofer-Institut für zerstörungsfreie
Prüfverfahren, IzfP
D-6600 Saarbrücken, FRG

INTRODUCTION

High quality heavy plates have to be free of any defects. The UT-inspection for internal defects is introduced as a standard. However, until now the inspection for surface defects is limited to visual inspection, magnetic stray flux - or eddy current inspection. The most sensitive technique is the magnetic stray-flux technique, but it is very time consuming because of the necessity to scan the whole surface. Using Rayleigh waves the inspection can be automated and performed at rolling speed. The sensitivity of frequency optimized Rayleigh waves is sufficient to detect a 0.3 mm deep model defect at a distance of 300 mm. The use of piezoelectric probes is limited by coupling problems. These problems are overcome by the use of EMAT's, which have been optimized with respect to probe size, sensitivity and wear resistance. For the automated inspection the ALOK-system has been adapted in a laboratory system to the surface inspection of heavy plates by Rayleigh waves. This equipment consists of an ultrasonic hardware device for fast data-acquisition and -preprocessing (essential data reduction) according to the ALOK-algorithm, and a computer to realize noise- and ghost - elimination as well as defect imaging and -reconstruction. Examples of the surface inspection of heavy plates using electromagnetically excited Rayleigh waves in connection with the ALOK data-acquisition and evaluation system are reported. The investigations were supported by the ECSC (European Community for Steel and Coal).

E.M.A.-TRANSDUCER FOR THE SURFACE INSPECTION OF HEAVY PLATES

The most sensitive ultrasonic technique for the NDT of surfaces is the inspection with Rayleigh-waves. These waves allow because of their guided character the inspection of large areas with one probe. Their application however is strongly restricted using piezoelectric probes due to coupling problems. These very severe problems for automatic inspections are overcome by the application of Electro Magnetic Acoustic Transducers (EMAT's). Their limitations for practical application are given by the very strong lift-off dependency of the ultrasonic amplitude. Because this lift-off dependency becomes stronger with increasing frequency (for higher sensitivity), an optimized ultrasonic frequency had to be found.

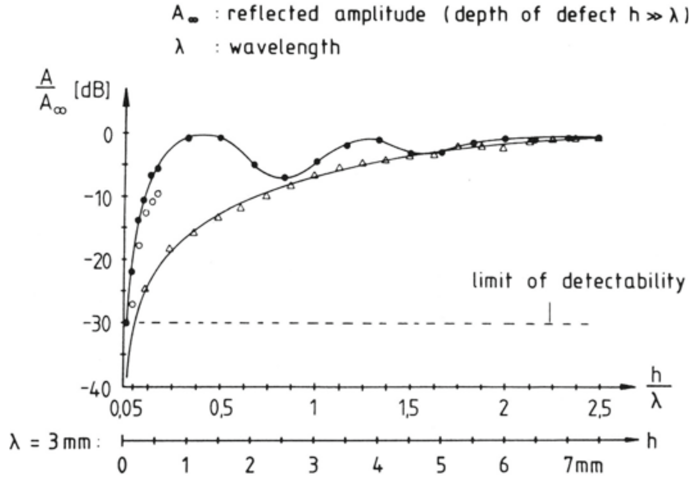


Fig. 1. Reflection of Rayleigh-(●), SH-(△) and creeping-wave (○) at model defects: amplitude as function of the depth

Figure 1 shows a diagram, which presents, based on experimental data, the dependency of the reflected amplitude on the normalized depth of model-defects (saw-cuts); depth h is normalized to the wavelength λ (1). It can be seen, that the limit of detectability is a defect depth of somewhat less than 10 % of the wavelength. If, as in our case required, a defect of 0.3 mm depth has to be detected, a frequency of 1 MHz (it means a wavelength of 3 mm in ferritic steel) is sufficiently high. At this frequency the lift-off dependency is 33 dB/mm. That means that because of the overall dynamic range of an EMAT of about 50-55 dB, the RF-coil has to be placed less than 0.5 mm from the surface of the plate. This small air gap can be increased by using higher magnetic inductions resulting in very large and heavy probes not applicable in multichannel equipment.

A solution of this problem has been found by a modified design of the RF-part of the EMAT (Fig. 2) (2). Instead of coupling the RF-coil via air ('air coils') into the material with a strong lift-off influence, a magnetic circuit consisting of a magnetic core and the specimen is used. The RF-coils are wounded on the magnetic core; the magnetic field of the RF-coil is guided by the core to the material. By an adequate shaping of the core, the coil can be placed with an arbitrary distance from the material. Fig. 2 shows in the lower part the realization of this concept. The magnetic core, consisting of a highly permeable material with a low electrical conductivity, is shaped like a comb. The coil is wounded on the teeth with alternating direction on adjacent teeth. Each coil produces a RF-magnetic field with alternating direction in adjacent teeth, so that alternating magnetic fields in the material resp. between the bottom of the teeth are produced, which induce the eddy currents. By this comb-shape of the magnetic core and the alternating direction of winding of adjacent coils, a spatial distribution of the RF-magnetic field in the material's surface identical to that of an 'air coil' wounded on a perspex or ceramic core is achieved (upper part of Fig. 2).

Fig. 3 shows three variants of the transducer which have been studied. The newly designed RF-coil and core can be operated in a magnetic bias field as well perpendicular realized by an electro- or permanent-magnet, as parallel to the surface of the test object. Mainly when working with a perpendicular magnetic bias induction the core material has to have a high saturation induction. Then the comb-core is a part of the magnetic

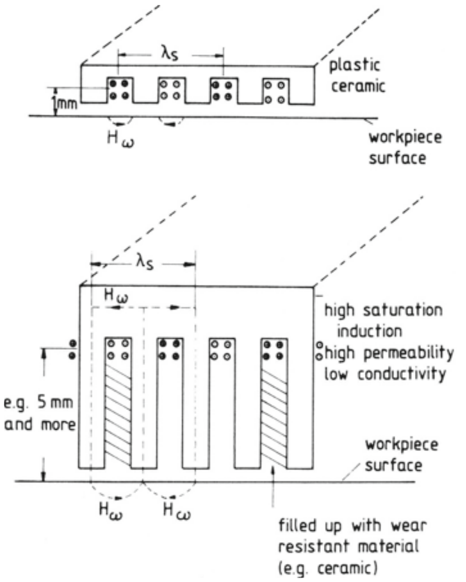


Fig. 2. Variants of the RF-coil

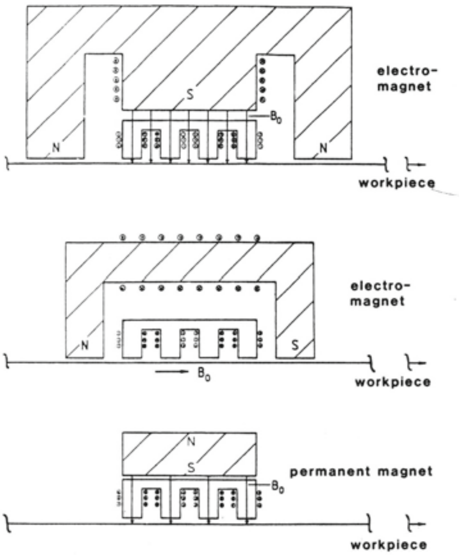


Fig. 3 Variants of the probe

circuit of the magnetic bias field resulting in a smaller air-gap than in the case of an air coil. This is a further advantage of the permeable core concept in contrast to the air coil; in this case the larger the lift-off of the coils, the larger becomes the air gap of the magnetic circuit of the magnetic field. Furthermore the comb core should consist of a material with low electrical conductivity to minimize eddy current losses in the core. All these necessary properties - high permeability, low electrical conductivity, high saturation induction - are not fulfilled by ferrites, usually used for the present task. Therefore the cores are built up by thin transformer sheets or by ferromagnetic powder composite material.

EXPERIMENTS AND RESULTS

Comb cores have been realized with a period a_s of 3 mm. To design an optimized transducer, the core for transmitting the ultrasonic wave has been investigated in a perpendicular magnetic bias field. The dependency of the excited ultrasonic amplitude (Rayleighwave, 1 MHz) in ferromagnetic materials has been measured as function of the peak to peak amplitude U_R of the transmitter current and the magnetic induction. As to be expected from the theory the ultrasonic amplitude increases linearly with increasing magnetic induction. This linear relationship is indicating, that the ultrasonic wave is excited by Lorentz-forces as exspected for 'air coils'. Fig. 4 shows that this is valid up to 0.65 T. Above this value the amplitude decreases, because the permeability of the core material decreases and the coil acts more and more as an 'air coil' with a large lift-off. This decrease of the permeability of the comb core becomes apparent by the decrease of the inductivity L of the coil, as shown in the same Figure. The magnetic inductions necessary to achieve maximal signal-amplitudes are low (<0.5 T), according to Fig. 4. Therefore small electro- or even permanent- magnets can be used. This fact leads to very small probes, see Fig. 5, which shows a probe with permanent magnet. The probe size is $60 \cdot 35 \cdot 25\ \text{mm}^3$.

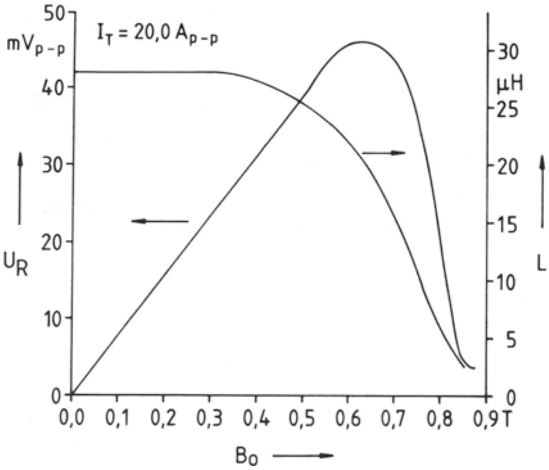


Fig. 4. Ultrasonic amplitude versus magnetic induction

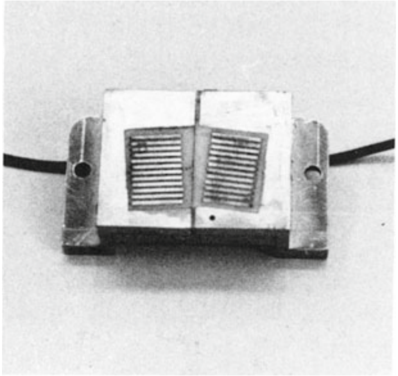


Fig. 5. Probe with permanent magnet

ELECTRONIC EQUIPMENT

For the application of surface inspection of heavy plates, a new laboratory device, called ALOK-4 (Fig. 6), and a electromagnetic ultrasonic T/R-unit were developed. ALOK is realized by a hardware-equipment for fast data acquisition and by a software-package for the imaging and evaluation of the stored data. In contrast to earlier ALOK devices, ALOK-4 performs the signal processing procedures by software.

ALOK-DATA PROCESSING

The ALOK-system uses for the interpretation of signals the time-of-flight locus curves that result if the ultrasonic probe is moved on the surface of the test object across a reflector within the inspected volume, respectively for the surface inspection along a defect on the surface (3). At equidistant probe positions, both time-of-flight and amplitude of the echo maxima within the RF-signal are recorded by the ALOK ultrasonic hardware equipment.

Dependent on size, position, and structure of a defect, the detected data lead to a characteristic time-of-flight pattern, that can be used to analyse the defect. For the surface inspection with Rayleigh waves, besides the time-of-flight of mode-converted waves, the amplitude is one possible piece of information to estimate out the depth of a surface defect. A rough determination of the depth of a surface defect can be achieved by amplitude calibration.

The ALOK-procedure performs the signal detection with respect to probe characteristics. The detection process is comparable to a recursive digital filter, which moves the typical pulse shape, emitted by the probe, across the received signal, filtering out all extreme values from the rectified RF-signal (Fig. 7). The probe-dependent parameters i and k of signal detection describing the resolution of the probe are rise- and fall-time of the envelope. The resolution of the total system is given by the damping of the probe. The parameters i and k are determined by a calibration process with a calibration reflector adapted to the inspection problem. The axial resolution which means the smallest

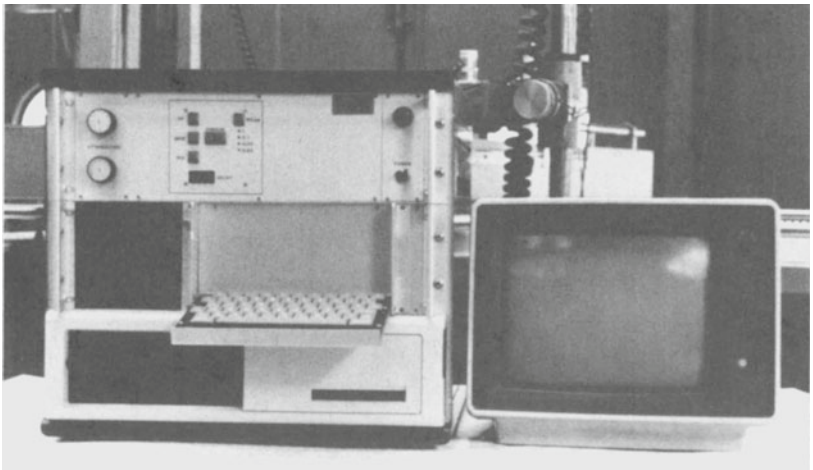


Fig. 6. ALOK-4 device

distance between two resolvable reflectors (with i<k) is given by

$$d = \frac{(k+1)*\lambda 2}{2} \tag{1}$$

For the electromagnetic Rayleigh wave probe used i is 4 and k is 5. Therefore, the resolution is according to (1) d = 4.5 mm for the 1 MHz EMAT.

The described procedure of signal detection allows data acquisition without amplitude thresholds, because noisy signals normally don't have the same typical pulse envelope as reflectors. Electronic and acoustic noise signals that are still detected can be eliminated subsequently, because they do not follow dynamic locus curves as shown in Fig. 8. By the aid of a noise elimination procedure, which is filtering out

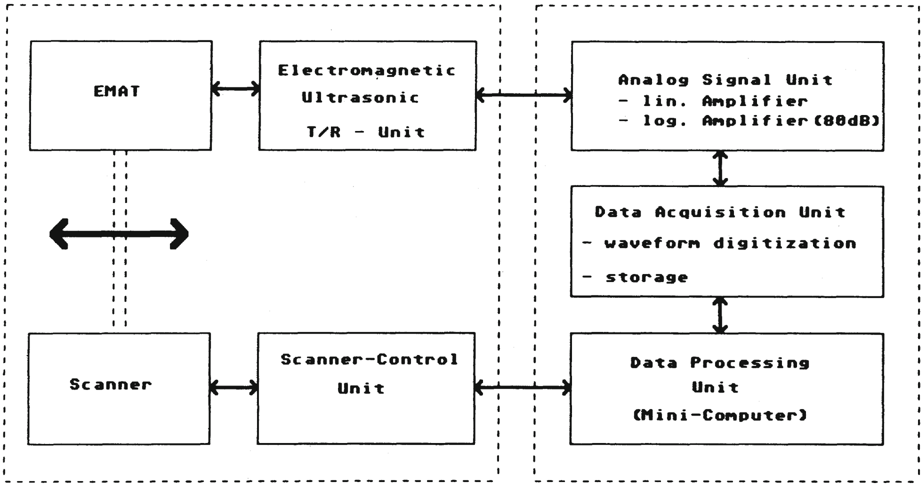


Fig. 7. Signal detection by ALOK-4

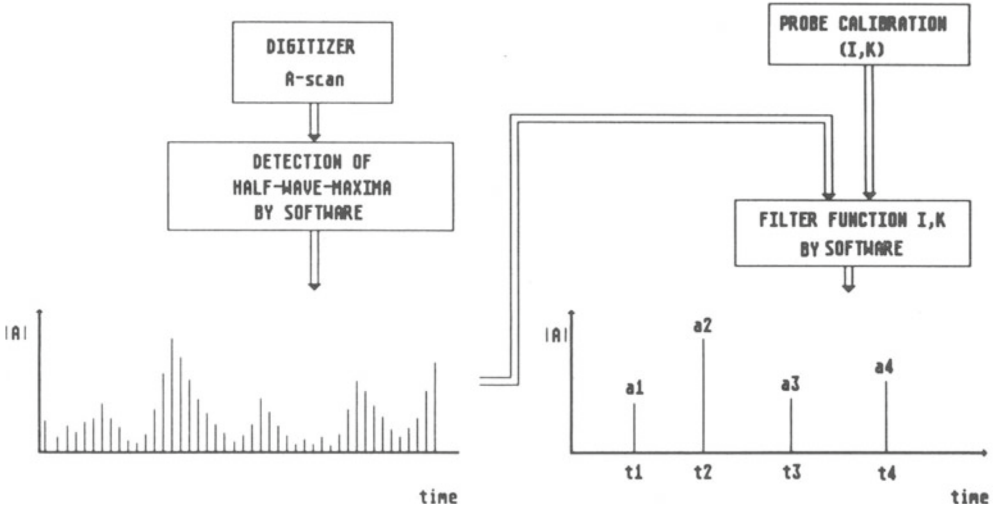
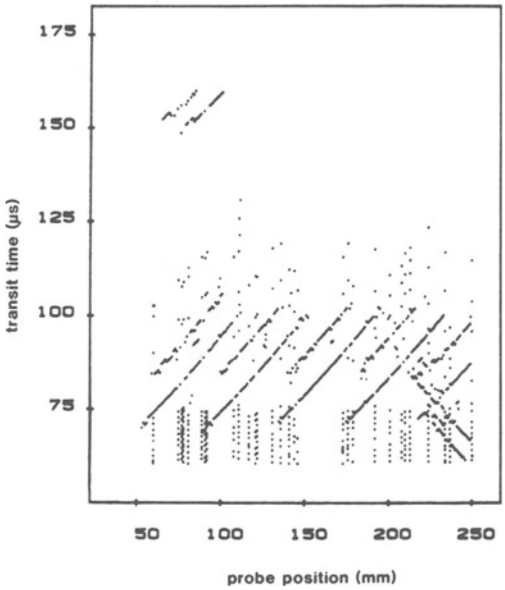


Fig. 8. Time-of-flight data
after preprocessing

Fig. 9. Time-of-flight locus curves after noise-elimination



time-of-flight locus curves typical for the applied inspection technique, we achieve an essential reduction of data (Fig. 9). In this context some identified boundary echoes (e.g. edge echoes) can be eliminated or marked by pattern recognition techniques. Because the data are stored as triples of position, amplitude and time-of-flight, this noise elimination leads to an artificial enhancement of the signal-to-noise ratio.

RECONSTRUCTION AND INTERPRETATION OF SURFACE-FLAW SIGNALS

The evaluation of transit time locus curves additionally allows the characterization of surface flaws, i.e. the reconstruction of flaw position, size and in some cases of flaw type. For a known sound velocity the time-of-flight describes the distance between the reflection point at the surface of the object and the position of the probe. The time-of-flight dynamic curve corresponds to the change of the distance and allows localization and sizing of the defect (4).

Within the ALOK-4 inspection system, two reconstruction methods can be performed for the surface-inspection. The first one is a simple geometrical reconstruction and the second is a video-SAFT-like pixel-reconstruction. Both methods show the result of a surface inspection in a C-scan. As for the geometrical reconstruction, the geometrical locus of points with the same time-of-flight is assumed to be a circle, the center of which is the beam entrance point. Searching for intersection points of circles corresponding to neighboured probe positions the reflector will be surrounded. Fig. 10 shows the result of the geometrical reconstruction for the example of two natural surface cracks (length 30 mm, depth 0.4 mm). The result is performed by superposition of different inspection techniques as 45°, 60° and 90°. The tips are given by the results of different inspection techniques. The length is obtained by a probe displacement parallel to the defect but with beam incidence perpendicular to the defect. The length of the flaw corresponds to the horizontal part of the time-of-flight locus curves (Fig. 11).

During the inspection of surface of heavy plates different types of possible flaws must be included in the classification, like longitudinal cracks, transverse cracks, crack-fields, stress cracks, scabs, rolling

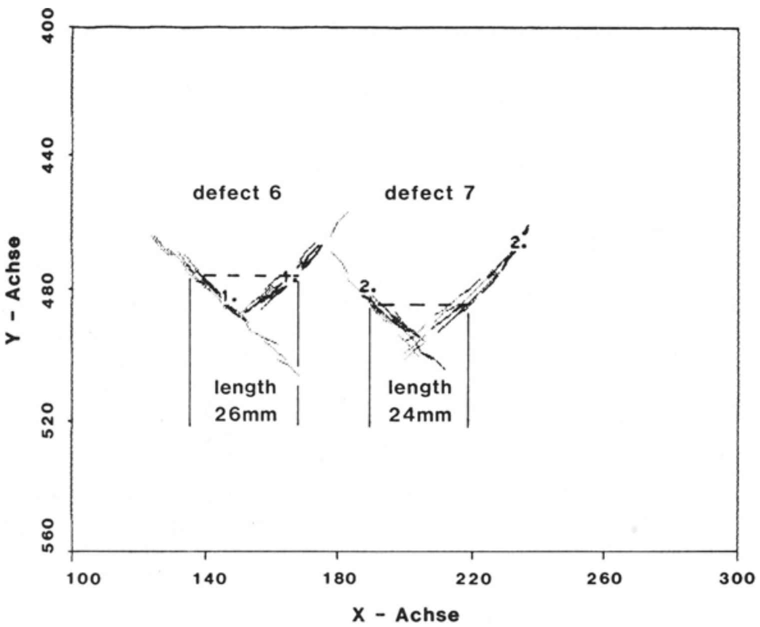


Fig. 10. Example of a geometrical reconstruction; superposition of pulse-echo 45°, 60° and 90° inspection techniques

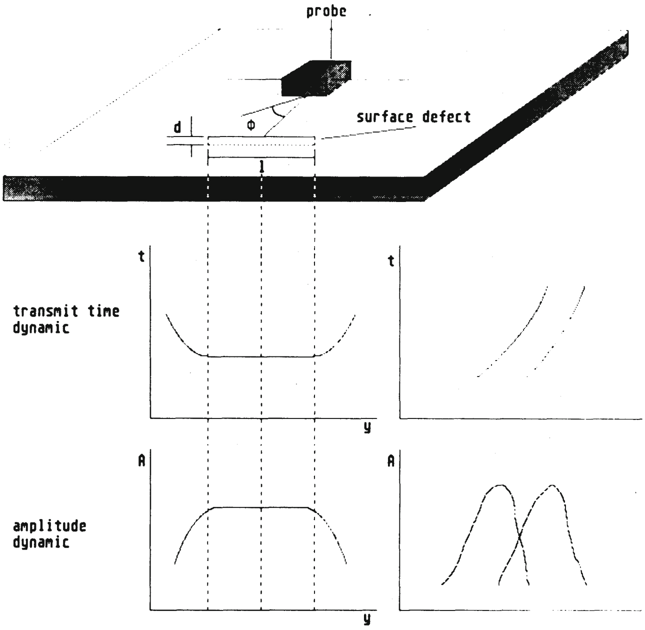
laps, scratches, and pores. Small defects in the range of 20 mm in the longitudinal and transverse direction can be localized by superposition of at least 3 inspection techniques (+45°, -45°, 90°). A statement on length in longitudinal direction is possible if tip-signals exist.

Defects with only a few mm in length and a depth of 0.3 mm can be localized at a distance of 300 mm between transducer and defect. The signal to noise ratio is then at least 10 dB. Surface defects like stress-cracks, cast-powder or rolling laps are normally widely spread defects. These defects can be described with the mentioned reconstruction methods in the whole size, or according to the contour. Cracks perpendicular to the surface show several time-of-flight locus curves, produced by a mode conversion of the Rayleigh wave at the defect leading to reflected signals from the opposite surface (Rayleigh-Shear-wave conversion).

To reconstruct the crack depth it is necessary to perform a defect calibration. Then the depth can be found by classification with respect to maximum amplitude. This method leads only to a rough statement for defect depth, because the amplitude is dependent on the surface quality.

CONCLUSIONS

A newly developed system has been demonstrated, which can be used together with an optimized electromagnetic Rayleigh-wave probe for the surface inspection of heavy plates. The probe has been optimized with



transverse scanning
angle: $\Phi = 0$
defect lenght l

transverse scanning
angle: $\Phi = 45$
tips of defect
depht = f(A), calibration

Fig. 11. Determination of flaw-length

respect to sensitivity, dimensions and wear resistance. Combined with the ALOK-procedure this technique can be applied for defect localization, sizing, and classification. The measurements showed, that at a distance of 300 mm between transducer and defect (0.3 mm depth, 6 mm length) the signal to noise ratio is 10 dB. With these results an inspection area of 300 mm can be covered.

It is planned for the future to develop a modular, high speed ALOK-system in order to perform an online surface inspection and evaluation within the production process.

REFERENCES

1. P. Höller, G. Dobmann, J. Salzburger, U. Coehne in <u>6. MPA-Seminar, MPA Stuttgart, 1980</u>
2. H.J. Salzburger in <u>4th European Conference on Nondestructive Testing, Conference Proceedings</u>, Paper SS02/P03 London, 13-17 September, 1987; to be published by Plenum Press
3. O.A. Barbian, B. Grohs, W. Kappes, and F. Höh in <u>Automated Nondestructive Testing</u>, Volume 4, edited by Warren J. McGonnagle, Gordon and Breach Science Publishers, 1983.
4. B. Grohs, O.A. Barbian, W. Kappes, H. Paul, R. Licht, and F. Höh in <u>Materials Evaluation /40/</u>, Jan. 1982