ABSTRACT. Within a know-how transfer project funded by the government conventional ultrasonic technique was replaced by phased array technique for automated round-bar testing. Instead of applying a great number of conventional probes to achieve acceptable volume coverage we used curved linear arrays. The benefits of phased array technique such as programmable skew angles, beamforming and beam positions, led not only to a significant decrease in inspection time, but also the number of probes could be substantially reduced. Finally, the testing parameters for a large range of bar-diameters could be adapted by software control instead of time-consuming mechanical replacement. The probe-design was carried out by a proprietary modelling program. Both the theoretical calculations as well as the latter experimental verifications revealed significant advantages of curved arrays versus the planar types. A radial oriented probe offers perfect adaption to the cylindrical shape of the specimen allowing wide variations of the sound field. Thus beam direction, beam size and beam position could be optimized with respect to a minimum of inspection cycles, as inspections have to be executed in-line during the production. A number of laboratory tests were carried out on special test components. In order to achieve an optimal performance of the reference rod we implemented three different types of reference reflectors: (i) flat-bottom-holes with diameters of 0.8 mm and 1.2 mm, (ii) side-drilled-holes with a diameter of 0.7 mm for the detection of volumetric flaws, and (iii) notches with a depth of 0.2 mm and 0.5 mm for the detection of surface-oriented defects. All laboratory tests were carried out with the COMPAS-XXL inspection system, a proprietary development of BAM.

Keywords: Ultrasonic Testing, Phased Array, Round Bar Testing

INTRODUCTION

Testing of semi-finished products such as rods is a standard tasks in the steel industry (Fig. 1). Semi-finished products provide the raw material for further production steps, for instance, in the automobile industry and are subject to very high quality requirements. A part of the requirement is to avoid material defects such as cracks or inclusions.

For this reason the manufacturers of semi-finished products are required to make certain their products are defect-free using non-destructive test methods as early as during the production process. Ultrasonic testing is a very efficient method that has been proved in industrial practice for many years. In contrast to X-ray testing, it enables automatic tests with a high throughput of test objects and provides test results in real time, i.e. instantly during the tests. Defects can be marked for rapid identification directly on the test specimen e.g. by paint pistols, during the tests.
Testing rods without rotating either the ultrasonic sensors (also called probes) or the test object represents the current state of the art. Several probes are arranged circumferentially within a water chamber through which the test specimen is moved axially by driving rollers at high speed (up to 2 m/s, see also Fig. 2). Thus the tested article is guaranteed to be scanned from several sides and a high degree of cover is achieved. Sound transmission and/or sound beam coupling to the test object can also take place without a water chamber using water jets, and so-called gap scanning is also feasible.

The so-called conventional ultrasound test technique is used where the ultrasonic sensors have fixed sound field parameters, which means that the acoustic irradiation angle, the focus depth range and the position of the sound beam are set by the physical design of the probe and/or the mounting plate and thus are unchangeable. The consequence of this is that up to 15 conventional probes are needed for an adequate sound covering. If a rapid change to other diameters is required using replaceable cartridges, then as many as 45 are needed [1].

**FIGURE 1.** Rods with different diameters (Courtesy of Karl Deutsch Company)

**FIGURE 2.** Cartridge with fifteen conventional ultrasonic probes (Courtesy of Karl Deutsch Company)
2. TEST CONCEPTS USING AN ULTRASOUND PHASED ARRAY
TECHNIQUE

A phased array consists of an emitter surface which has a one- or two-dimensional
arrangement and is divided into single small components. Such phased arrays function
both as transmitters and/or receivers using a control with different delay times and
different allocations, and provide the following key possibilities for electronic sound field
control: swing, focussing, offset and creation of the sound beam [2].

One-dimensional phased arrays, also called linear arrays, have been employed
extensively in practice. The number of transducer elements in the probes marketed by
commercial vendors varies from between eight to a few hundred individual components.
Different types and geometrical arrangements are available: in addition to transducer
elements with flat coupling surfaces for contact and submergence technology, there are
special forms with curved transducer soles e.g. semi- or quarter-circle arrays.

Two different concepts have been developed and tested. The concept tested first is
based on standard phased array probes with 16 elements and a flat transducer surface. They
offer the advantage of easy availability and favourable procurement costs. Eight such
phased array transducers were arranged in a circle around the test object, which enabled a
complete covering of the test volume both for vertical irradiation and for testing the
boundary region at 45° (Fig.3). The disadvantage of this concept however, is its
unfavourable geometrical arrangement (flat emitter surface facing a round test specimen),
which results in a decrease in sensitivity and thus in a poor signal to noise ratio (SNR).

This disadvantage was overcome by the use of linear transducer arrangements with
curved transducer surfaces (Fig.4). Quarter-circle arrays with 128 elements, a radius of
curvature of 60mm and an aperture angle of 100°, as offered by many commercial vendors,
increased the SNR in relation to flat forms by up to 20 dB and significantly reduced the
necessary number of sensors. The electronic offset of an active phased array of 16
elements (‘virtual probe’) over the total transducer enabled a program-controlled
adjustment of the rods with different diameters as well as optimization in terms of the
number of test cycles and the degree of coverage. In addition, it was possible to make
changes to the electronic sound beam such as angle, focus and beam width control in a
program-controlled way.

FIGURE 3. Test concept using eight linear phased array probes with flat transducer surfaces
3. MODEL CALCULATION

The advantages stated above led to the decision to implement the test concept using quarter-circle arrays. Probe optimization as well as determining the suitable sound field parameters was performed using the BAM-proprietary modelling program Array-Calculus [3] (Fig.5). A probe type with 128 elements, 5-MHz transducer frequency and an element distance of 0.84 mm provided the best compromise between cost, resolution and test sensitivity. An arrangement of up to four such probes ensured sufficient overlap and thus a complete covering of the test volume.

FIGURE 4. Test concept using a quarter-circle array with 128 elements

FIGURE 5. Sound pressure as function of the position within the rod for different broadness at the sound beams
4. EXPERIMENTAL TESTING

Experimental testing was performed at the laboratory scale on rod samples in which artificial defects were made. Three rod samples with diameters of 20 mm, 40 mm and 60 mm were tested, each containing a set of 1.2-mm and 0.8-mm dia flat-bottom holes (FBH) of different depths (Fig.6). In order to come as close as possible to the conditions in practice, some of them were offset and supplemented with horizontally drilled holes of 0.7 mm diameter drilled on their faces. Also, two grooves with dimensions of 12 mm x 1 mm and depths of 0.5 mm and 0.2 mm were applied on the surface to investigate the boundary region.

The measurements were carried out using different types of focusing, i.e. different sound beam widths, with the aim of verifying the results of the model calculation. They were determined with the help of the -6 dB drop and provided a good agreement, i.e. the maximum deviation between the modelled and measured values was as low as 0.4 dB. In addition, similar measurements were carried in order to determine the maximum permissible lateral incidence angle. This served to determine the offset positions of the phased array for the central reflectors.

The measurements using a non-focussed sound field resulted in a maximum permissible gap of 7 elements between the active phased arrays, where a measuring point distance of 2 mm was maintained. Altogether 6 positions within the total transducer were tried per probe, thus flat-bottom holes with both 1.2 mm and 0.8 mm diameter were detected at different depths with a sufficiently suitable SNR (Fig.7).

**FIGURE 6.** 60-mm diameter rod test sample with artificially placed test reflectors
5. DETERMINATION OF THE MAXIMUM FEED RATE

Determination of test density is based on the selected axial and radial repetition rate [4]. With the help of experimental investigations on the test samples, the number of test cycles necessary and thus the maximum attainable test speed (rod feed rate) was determined. The maximum time of flight of the sound, specified by the physical limits, can be obtained as shown in Fig.8:

\[
\cos \alpha = \frac{r}{d} \rightarrow d = \frac{r}{\cos \alpha} \rightarrow d = 42.42 \text{mm}
\]

<table>
<thead>
<tr>
<th>Time for return journey in</th>
<th>Time for return journey in</th>
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<tbody>
<tr>
<td>water</td>
<td>steel</td>
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<tr>
<td>( \frac{s}{t} )</td>
<td>( \frac{s}{t} )</td>
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<tr>
<td>( t = \frac{2 \cdot 0.030m}{1480 \text{ m/s}} )</td>
<td>( t = \frac{2 \cdot 0.042 m}{3250 \text{ m/s}} )</td>
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<tr>
<td>( t = 0.000041 \text{ s} )</td>
<td>( t = 0.000026 \text{ s} )</td>
</tr>
<tr>
<td>( t = 41 \mu s )</td>
<td>( t = 26 \mu s )</td>
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</table>

\[ t_{\text{total}} = t_{\text{Water}} + t_{\text{Steel}} \]
\[ = 41 \mu s + 26 \mu s = 67 \mu s \]

FIGURE 7. Detection of offset reflectors on a 60-mm dia rod test sample

FIGURE 8. Schematic of an automatic rod testing equipment with two quarter-circle arrays
Specifying 2 x 12 test variation options for the boundary region and 12 test variation options for volume testing results in a maximum feed rate of 1 m/s for if an axial measuring point distance of 3 mm has been selected. This can still be increased by combining the test variation options for the boundary region using ‘double sound beam technology’. However, an improvement in defect detection in the rod volume using additional test variation options with an inclined irradiation results in a reduction of rod feed rate or decrease in axial resolution.

6. SUMMARY

Testing round rods of diameter ranging between 15 mm and 80 mm is feasible using quarter-circle arrays with a 5-MHz transducer frequency, a 60-mm radius of curvature and 128 elements. As proved by model calculations and experimental investigations at the laboratory scale, flat-bottom holes with FBH 1.2 mm and 0.8 mm as well as grooves with 0.5 mm and 0.2 mm were detected with an adequate SNR. Carefully selecting the distance of measuring points results in a feed rate of up to 2 m/s – assuming an axial sound beam width of 6 mm, and this was determined both by model calculation and experimentation.

An automatic test unit based on the results presented here was constructed using a Compas-xxl developed by BAM as a control unit. Thus a concept was realized where, by using two axially shifted quarter-circle arrays, sufficient covering for both volume and boundary testing could be guaranteed (Fig.9).

**FIGURE 9.** Schematic of an automatic rod testing equipment with two quarter-circle arrays

**REFERENCES**