Automated Testing of Bar Stock Materials for Aerospace Applications with Advanced Automation Features

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Abstract. Ultrasonic Testing of Bar-Stock material has gained a major boost in testing quality by replacing the test-techniques with single crystal transducers to techniques which apply by Phased-Array Based solutions. Typical methods with single crystal transducers either apply rotary heads, which are typically applied, if the test is installed within the bar finishing line and immersion tanks, which are applied when a higher degree of test accuracy is required.

A most interesting realization of this test is the so called ROWA arrangement, which combines the simplicity of a rotating water jacket, as it is also generated by rotary heads, with encircling phased array probes. Doing this, on the one hand, one preserves the excellent coupling features of the rotary head. On the other hand, the phased-array Scan solution eliminates the need for moving parts, which significantly reduces the service effort. From the pure detection perspective, the cylindrical probe geometry concentric to the material generates a most optical geometric situation, which explains the excellent defect detection characteristics.

With respect to applicable material specifications and standards, the adjustments and calibrations of the plurality of virtual probes and amplitudes are an important quantity to track, since the test homogeneity and completeness is determined by these parameters. Dependent on the specification, the tests and documentations can be thorough.

To support this and obtain a most complete accordance with standards, we present a fully automated Phased Array system which does not only include the calibration of virtual probes but also of the Time Corrected Gain functions to homogenize the test sensitivity over the full material cross-section. In addition, advanced measurements like the ripple and uniformity test are fully implemented allowing the system to be compliant with a large number of specifications, in particular from the high demanding segment of aeronautic applications. The features are illustrated with aid of examples from daily operation.

Keywords: Ultrasound, Phased Array, Aerospace, Bars, Steel
Introduction

Today, a large number of advanced technological applications deal with steel bars as a key component within their products. Among the many examples, aerospace and energy products typically require highest degree of pureness and absence of defects inside the material as well as optimum conditions in terms of grain structure, size and texture homogeneity. Especially for highly stressed components such as bearing balls or turbine blades, the rolled bar is the product of choice.

One of our most critical products in regard to internal defects requirements and safety requirements is material which is used in the aviation industry. The testing on smallest internal defect sizes is prescribed in customer specifications using traditional ultrasonic immersion tank systems.

Böhler has world’s first steel manufacturer approval for ultrasonic phased array continuous test facilities for the testing of steel bars which is used by the manufacturers of aircraft engines (Pratt & Whitney, GE - Aviation, Snecma, Rolls Royce etc.).

Ultrasonic phased array technique

Operating principle of the ultrasonic phased array technique for round bars

Either systems with mechanical rotating transducers or systems with in the sound field overlapping PVDF probes which have only a low, inadequate sensitivity are mostly used for conventional ultrasonic testing equipment for rolled steel bars and pipes. The company Böhler uses four 90° “phased array probes” in the "phased array technique". These phased array probes consist each of 128 or 224 transducer elements, where each one is electrically wired so that each element can be stimulated as an ultrasonic transmitter and can be used as a receiver. Apertures of up to 32 transducer elements form a virtual probe for testing.

A serial transmitted pulse of the transducer elements in the multiplex technique generates a linear scan on encircled arrays, a virtual rotating sound field. The aperture step size determines the virtual rotation speed.
By use of delays in the transmission pulse to the transducer elements of a virtual probe in a specific order, the sound field can be formed. Through this electronic forming of the sound field, it is possible to generate an arbitrary angle in radial direction, as well as a focusing of the sound field. After entering the parameters such as probe type, bar diameter, angle in the bar, focal distance, etc., the software of the testing system calculates the necessary delays.

For coupling of the ultrasound in immersion technique, the so-called "ROWA"-principle (this means rotating water jacket) is used. The phased array probes are located in a chamber in which water is injected by tangentially mounted nozzles. This produces a rotating water jacket (a water pipe). The inner diameter of the pipe is dependent on the amount of water that is injected and is set so that it is only marginally less than the diameter of the steel bar to be tested. This results in marginal water displacement by entry of the bars into the water chamber and thus not disturbing air bubble inclusions or water turbulence, which could have a negative effect on the water coupling. The "ROWA"-principle ensures extremely low untested bar ends with a length of 15-20 mm at a feed rate of up to 0.8 m/sec.
Calibration of the system

Ultrasonic test block

Test block with precisely defined flat bottom hole diameter, depths and distances are required for the sensitivity adjustment. Adherence to the close tolerances for hole diameter, flatness of the flat bottom, depth and perpendicularity of hole etc. are to provide appropriate evidence (such as optical microscope measured replica impressions of holes).

Axial and radial measuring of the sound field geometry

For the determination of feed rate, scan index, pulse repetition frequency and for the probe ripple and uniformity test, it is required to measure the sound field geometry in axial and radial direction. This has been done on the basis of flat bottom holes in different depths with test blocks and digital measuring instruments (dial gauge, digital angle gage or encoder). The sound field geometry was measured at minus 2 dB, minus 3 dB and minus 6 dB. The smallest, measured value in the axial direction is used for the calculation of feed rate, pulse repetition frequency and scan index. The smallest value in the radial direction determines the step size.
PLC controlled test block manipulator for measuring the axial or radial sound field dimensions

Figure 5: Example of sound field measurement

Axial sound field dimension of an 0.8 mm flat bottom hole

Balancing of virtual probes

To set the individual virtual probes to the same sensitivity, a balance of virtual probes is performed. The balancing is performed on a flat bottom hole at defined depth which must be moved over the whole effective range of a phased array probe. The test system software automatically corrects the sensitivity of the individual virtual probes on the basis of the flat bottom hole reference echoes. The balancing has to be repeated so often until the sensitivity difference is within a defined limit (e.g. ≤ 1 dB).

Figure 6: Example for balancing of virtual probes
DAC – Distance Amplitude Correction or TCG – Time Corrected Gain

The variations in sensitivity are compensated by appropriate TCG curves or distance amplitude corrections. This is possible under the application of reference test-blocks as described in Figure 4. For each defect at a certain depth, a TCG-Point is inserted at exactly the position of the time-of-flight of this defect. The Gain Value associated with this point is set in order to achieve a predefined the amplitude of the relevant defect at this position, typically 80%. If this is carried out for all defects within the specification of the system, the complete TCG curve builds up and harmonizes the test sensitivity in beam direction with respect to the real situation and without assumptions or simulations.

Automated calibration with the PLC controlled test block manipulator

Adjustment and periodical Systems-checks of a Phased-Array Systems can be time-consuming and require a high degree of knowledge and experience of the operating personnel. In particular, positioning of the small reference defects with regard to the virtual probe is a major requirement and crucial for the accuracy of the measurement process. Originally, manually operated manipulation systems have been applied, to simplify handling, in particular of heavy pieces and increase accuracy and repeatability. To measure sound field extensions in radial and axial directions as well as test homogeneities with sufficient accuracy, the mechanical motions of the test manipulators have been tracked and imported into the inspection system.
Features of automated bar manipulators

Within a project between Böhler and GE S&IT an automated bar-manipulation system was developed, with special respect to the requirements of standards and specifications for steel products in Aeronautics. Test bars are mounted in this system, using an accurate axial positioning scheme and allowing the manipulator system to position and reposition defects to the ultrasonic transducers in a reproducible way and applying absolute coordinates. For each reference piece, the precise positions of the reference defects are entered into the instrument Software. To avoid interactions with other defects, additionally the characteristics of the measurement gates can be inserted into the software with respect to the defect to be adjusted.

The manipulator itself is driven by a PLC system, which communicates with the Software of the inspection system. Defect Positions are transferred to the PLC, which then takes care of positioning the reference piece in a correct way and allow a meandering adjustment process for all the virtual probes. Optimizations are acquired within a special “Teach”-Mode and stored within the database to make it easy to add novel test-pieces and geometry.
Automated aperture adjustment

To carry out the automatic aperture adjustment, the operator chooses the appropriate Reference defect used for the calibration selects the ultrasonic probes and, if required, activates the Meander function. The manipulator then moves the defect to the correct position and, if ready, the UT-Software starts the adjustment procedure. Within this procedure, the echoes from the reference defect with respect to each virtual probe are recorded, while the mechanical movement of the reference defect with reference to the probe takes place. When the mechanical movement has finished, the channel gains of the virtual probes are adjusted depending on the recorded values acquired before. In subsequent steps, this process can be repeated, until a predefined repeatability is achieved. Typical scenarios require for example repeatability within ±0.5dB.

Automated TCG Adjustment

TCG is a common feature in automated materials testing to assure the test homogeneity over the depth of testing. Anciently, TCG values were often derived from manufacturer’s data or DGS diagrams, however, this is not of sufficient accuracy as required by actual standards. Instead of this, today’s reference pieces show up with reference defects in different depths depending on the specifications to be tested to. Since the depth of the defect is a feature that is anyway entered into the Inspection system software, in an equivalent way to the channel adjustment process, the TCG curve can be adjusted.

If one assumes as an example to have defects at positions 1/4 D, 1/2 D, 3/4 D and at D-3mm, just before the back wall (see Figure 11), the adjustment process works in the following way: first, the appropriate reference defect is position accurately with respect to the ultrasonic probe. After that, the gate settings are adjusted appropriately in order to avoid false measurement. Then the adjustment process is started, where the manipulator moves or meanders the reference defect along the field of influence of the ultrasonic transducer and the Inspection software records the Amplitude values and the positions of the echoes from the reference defects. After the movement of the manipulator is complete, the appropriate TCG point is filled with the correction gain for predefined amplitude and the correct depth. This is equivalent to the requirement of having a TCG point at the position of the reference defect. The same procedure is then repeated for the various defects in different depths and of course for all ultrasonic transmitters applied for this inspection.

To simplify the overall process, the adjustment processes of channel gain and the TCG can be combined, since they are typically based on the same reference defects and share a common acquisition scheme.
Determination of Tolerances measuring Ripple and Uniformity

As all technical processes, Ultrasonic Testing shows up certain tolerances during the test. In order to assure the quality of the test and in consequence of the material, it is important to understand the tolerances and determine the deviation over the complete range of the test. The measurement of ripple and uniformity gives detailed information on the system.

To carry out a ripple and uniformity measurement, three steps are necessary:

1. For one Phased-Array probe, an angle resolved measurement of all signals of its virtual probes needs to be made. This is done by moving the reference defect to the maximum of the first virtual probe and use this as the zero point of the measurement. Then, for fixed angle steps from typically \(-x\) degree to the total scan-angle - end + \(x\) degree. A good value for \(x\) is 9d.degree. The difference between minimum and maximum signal over the total scan angle range is the ripple of the probe.

2. Without changing the zero degree point, the reference defect is moved to the next virtual probe and the same measurement as for probe 1 is made. This is done for all probes of the system, so the overall angle of 360° is covered. The difference between the minimum and the maximum signal over 360° is the uniformity of the Testing system.

3. To cover the full body of the test, the procedure is repeated for flat bottom holes of various depths. The Procedure is not dependent on the type of test, because the evaluation gate is used in the same way as during the test. If the angle test is applied, the evaluation gate of the appropriate channels is used to collect the ripple and uniformity data.

To make the test as reliable as possible, a test bar manipulator is needed. The manipulator allows to rotate the bar for 360 degrees and to translate the bar from the first probe to the last probe. The measurement itself is controlled by a special module of the testing software. The change of the angle is automatically monitored and evaluated for the correct position. After positioning, the measurement process is started and the Data is
collected. In a semiautomatic fashion, the complete Angle of 360° and complete ensemble of Phased Array Probes is scanned and evaluated. The Ripple and Uniformity values are calculated automatically after the measurement process and can be printed for documentation purpose.

Automated Probe Ripple and Uniformity Test

One major feature of having a test manipulator is to be able to carry out a Probe Ripple and Uniformity Test in an automated way. Probe ripple and uniformity is a major tool to characterize the sensitivity and test homogeneity of an ultrasonic inspection equipment and plays a major role in the qualification process of the ultrasonic equipment towards high level application standards, as they are required by many standards from the field of aeronautics, but are also sketched in the forthcoming PA Application standard ISO 18563-3.

The Probe Ripple and Uniformity test requires a sufficient accuracy of all components involved. Using the automated Manipulation system, the test can be carried out easily and in a reproducible way. UT Software and Manipulation system interact here in position encoded fashion to be able to correlated the results and obtain the maximum intensity within the volume. Figure 12 shows the result of a typical Ripple and Uniformity test: For one of the defects illustrated in Figure 11, the full cross-section is scanned and the overall amplitude is recorded with respect to the angular position of the virtual probe.

The difference between the absolute Minimum and the absolute Maximum over 360° is the local Ripple and Uniformity value for the defect in the specified depth.
Successively, the procedure is repeated for all of the other defects in various depths, and the local Ripple and Uniformity Values combine to the overall Ripple and Uniformity Value. It can be regarded as a characterization Value of the Test Homogeneity. Since the smallest Amplitude with respect to the defects is known, one can make sure to amplify the system appropriately, i.e. in a way that the lowest amplitude still provides an Alarm as required by the standards.

Connection of Ripple and Uniformity with ISO 18563-3

Contrary to single-crystal ultrasonic applications, whose test properties are mainly governed by the geometric and acoustic parameters of the transducer itself, Phased-Array system allow to electronically varying the characteristics of the ultrasonic beam. As a consequence, procedures as e.g. defined in EN 12668-2 which record the acoustic sound-field, are not meaningful any more. To secure the application performance, the beam qualification must follow the setting of the instrument. The recently released standard ISO 18563-3 aims to create a reproducible mechanism and procedure to solve the above described discrepancy. Despite of the explicit exclusion of encircling arrays in the standards, the general procedure can be applied. To do this, it defines two Groups with different purpose:

<table>
<thead>
<tr>
<th>Name</th>
<th>Content</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1 Tests</td>
<td>System Qualification for a particular test</td>
<td>Prove the system performance for a specific test situation</td>
</tr>
<tr>
<td>Group 2 Tests</td>
<td>System Integrity Check</td>
<td>Create a system follow up sheet and carry out test to secure the system performance has not degraded</td>
</tr>
</tbody>
</table>

For the ROWA example, to qualify the system, the Group 1 tests would have to be carried out. These require:

<table>
<thead>
<tr>
<th>Number</th>
<th>Feature</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.2. Elements and Channels</td>
<td>Check for false cabling</td>
<td>Done in Production</td>
</tr>
<tr>
<td></td>
<td>Element Sensitivity Variation</td>
<td>Done in Production, Re Measurement with System possible</td>
</tr>
<tr>
<td>8.3 Beam Characterization for Immersion Probes, instrument configured.</td>
<td>Absence of saturation</td>
<td>Directly visible in UT Software</td>
</tr>
<tr>
<td></td>
<td>Angle of Incidence</td>
<td>Measure with test Notch and encoded Manipulator</td>
</tr>
<tr>
<td></td>
<td>Sensitivity along Beam Axis</td>
<td>From TCG Measurement, also fully in Ripple and Uniformity Test.</td>
</tr>
<tr>
<td></td>
<td>Beam Dimensions</td>
<td>Certificate Measured in Ripple and Uniformity Test.</td>
</tr>
<tr>
<td>8.4 Imaging Check</td>
<td>Check positions in S-Scan, E-Scan, and Dynamic Check</td>
<td>Features on 2D online images like E-Scan or S-Scan are not applied in this TM, only positioning and amplitude accuracy in dynamic test to be considered. This is subject to the commissioning of the machine.</td>
</tr>
</tbody>
</table>
One can see that the most critical components of the desired features are clearly attributed to the operation of the manipulator and the Ripple and Uniformity check. For Group 2 checks, which occur after machine commissioning, this will behave very similar:

<table>
<thead>
<tr>
<th>Number</th>
<th>Feature</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.2</td>
<td>Visual Inspection</td>
<td>Check probe Surface, cables etc. for damages</td>
</tr>
<tr>
<td></td>
<td></td>
<td>To be done regularly</td>
</tr>
<tr>
<td>9.3</td>
<td>Relative Element Sensitivity</td>
<td>Element Sensitivity Variation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Re-Measure with system, target: 9dB max. Variation. Element compensation is possible, but not recommended.</td>
</tr>
<tr>
<td>9.4</td>
<td>Linearity</td>
<td>Standard Vertical Linearity on Virtual Probe Base</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Can be carried out manually for one virtual probe.</td>
</tr>
<tr>
<td>9.5</td>
<td>Absolute Sensitivity of virtual Probe</td>
<td>Carry out Adjustment in control Mode</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adjustment procedure is called on regularly base. The absolute sensitivity is recorded, compare to absolute Value from first measurement</td>
</tr>
<tr>
<td>9.6</td>
<td>Relative Sensitivity of virtual Probe</td>
<td>Carry out Adjustment in control Mode</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adjustment procedure is called on regularly base. The absolute sensitivity is recorded, compare to absolute Value from first measurement</td>
</tr>
<tr>
<td>9.8</td>
<td>Angles of Refraction</td>
<td>Measure with respect to reference defect</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Carry out Ripple and Uniformity measurement. From sensitivity maximum angle of Refraction can be calculated, if needed(^1). Full Ripple and Uniformity test provides better characterization.</td>
</tr>
</tbody>
</table>

Those who are familiar with the industrial procedure of the qualification of an automated testing machine will recognize many of the above points as classical components of a commissioning record. The only new one is the explicit test homogeneity, whose main purpose is, to record the minimum signal obtained during a test to allow the appropriate correction. As described above, Ripple and Uniformity produces exactly this information. In addition, the re-measurement of the true beam characteristics with the Ripple and Uniformity algorithm ensures the test homogeneity to remain within a certain range. This even included the existence of dead elements on the probe, since the defect reflectivity is proven within the complete volume of the test piece.

\(^1\) For an E-Scan with cylindrical parts, the angle of refraction is not a very characteristic feature. Ripple and Uniformity gives far more results, since it re-measures the real beam characteristics and depicts the deviation in sensitivity over the complete cross-section
Conclusions

The phased array testing with encircled array shows excellent results in near- and far resolution, as well as the defect detection limit and the signal-to-noise ratio. Despite the fact that the requirements of individual aviation customers for the approval process and the periodic performance check of the phased array systems is very hard and complex, comparing the throughput rate of the phased array technique with the classic immersion tank technique, the phased array technique is a great economic benefit. The plc controlled test bar manipulator is helpful for the operator to keep the time for calibration and performance checks short. Though not foreseen to be within the scope, a system as described herein could deliver all the necessary information for a qualification in alignment with ISO18563-3. This proves the capabilities of modern testing machines and how their reliability can be assured, even under the assumption of complex and demanding standards as they are in use for Aviation related products.

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