Testing of forged bars with phased arrays for aerospace applications

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Abstract
Forged bars within a diameter range of 80mm up to 420mm are a key semi-finished product for the implementation in highly stressed environments, like engines or turbines. The major advantage of these parts can be attributed to the unique quality in terms of grain size being obtained by the high level of mechanical deformation, the widely variable alloy structures and near net shaped dimensions. Herein, a fully automatic test system for body, surface and sub-surface inspection is presented, with special respect to relevant specifications of products for aerospace applications. Therefore, phased-array probes have been designed to test various zones of the material. Results of defect recognition and productivity will be presented in comparison to standard immersion techniques.

Keywords: Ultrasound, Phased Array, Aerospace, Billets, Steel

1. Introduction

Today, a large number of advanced technological applications deal with steel billets 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, like turbine shafts, or bearings, forged billets are the product of choice.

They are typically forged from casted blocks to long round or square shaped billets. Already the quality of the blocks can be kept very high, for example by various re-melting techniques as can be seen in Figure 1, the high deformation degree that can be established by the forging process with a rotary forging machine with a maximum forging force of 2,000t allows excellent texture homogeneity and small grain sizes.

The latter is a key requirement to allow a non-destructive test for impurities inside the material, since it allows testing at high sensitivity levels with low grain noise. So apart from the excellent mechanical properties, the degree of testing can be done in order to detect small indications as well. The surface condition of the billets has also very high influence on the test results.
2. Automated Inspection Concept

2.1 Mechanic setup of test equipment

In general, two ways of testing need to be accomplished: the most important test is carried out with compression waves in a perpendicular arrangement. This test targets inclusions either axially extended or point-like localized in the material. The typical reference defects applied are flat bottom holes, starting from 1/64” (0.4mm) and then increasing in steps of that. For this particular application, the detection limit starts at 2/64” (0.8mm) flat bottom hole diameter, but can be adjusted to larger sizes if necessary.

Defects in these products and their occurrence in the product are related to the block casting process on the one hand and the forging on the other hand. Common appearances are near surface defects, where the block starts to solidify and the inclusions don’t have time to escape in the liquid. Other typical defects are real core defects, which can mostly be attributed to the solidification process itself. A third example of typical defects are surface breaking cracks, which come up mostly after the heat treatment process. All of these defects enter common standards applied within the industries.
The test concept was designed for round billets in peeled condition in order to implement a special test system for the defects described above. To achieve this, a helical test scenario was chosen. Figure 2 illustrates the general System:

1. The billets are loaded from a separation tray into a rotation line, which consists of several posts of double rolls, whose distance is designed in order to carry the smallest and the largest billet with respect to a stop position.
2. The billets are set in rotation. The conveyor has a small pitch, so the bars linearly move into one direction, until they reach a stopper, which fixes them in axial position.
3. A gantry setup was designed above the rotation conveyor. On the gantry, a carriage is mounted which can drive linearly along the gantry, thereby covering the complete length of the billet.
4. The test-mechanics is mounted at the carriage and can move with the carriage along the billet.
5. While the billet constantly rotates at a fixed speed, the carriage moves to the start position of the billet. Here, the first test system is set to the billet surface.
6. After one rotation, the carriage is moved linearly along the billet, until it reaches the end. There, another rotation is carried out. The result is a helical test track, which covers the billet surface.
7. If more than one test system is used, they are set to and unset from the billet appropriately.
2.2 Principles of testing

All Test systems are mounted in so-called probeholders, as can be seen in Figure 4. The probeholder consists of a mechanical system which allows a sufficient degree of freedom to move and tilt in all directions and by that to allow the test-system to follow any of the movements of the billet. These movements occur by deviations of straightness in the billet, which start to move when the billet is rotating.

1. The first probeholder carries the Eddy Current testing system. It consists of an arrangement of 7 coils, which are linearly oriented along the axis. The test track distance given by that is 10mm, so a smallest defect of 5mm length can be detected.
2. The Probeholders 2-4 carry ultrasonic probes.
One key issue in round-billet ultrasonic testing is the defocusing effect, which is induced by the refraction from water to steel. In combination with the relatively large diameter of the billet, it cannot be expected that one probe is sufficient to ensure the sensitivity level across the circumference. To avoid this, two zones have been selected, which are aligned at the particular requirements of the appearance of defects. Figure 5 illustrates the working principle of the ultrasonic test.

The first probe starts testing at about 20mm and extends its inspection zone at least to the center of the billet. It therefore is used to look as well to inclusions in the core itself to the surface, but does not need to cover the very near surface zone. This allows using a moderate frequency for this probe and a sufficiently large virtual probe, which is needed in order to detect small defects inside the material.

At the surface, a different probe is used. It combines a higher frequency and a cylindrical focus with a smaller probe surface. This gives the framework to detect small defects near the surface. The limit of detection is about 1/8" (3.2mm) from the front surface.

In order to support the Eddy current test, two ultrasonic probes are aligned such, that the ultrasound refracted into the material propagates therein at an angle of 45°, i.e. a shear wave is excited, which is then calibrated to the same notches, which are used for Eddy current calibration. But contrary to Eddy current, they allow to detect as well defects below the surface. By that method, the test-integrity for crack detection is enhanced with respect to non-surface breaking cracks, which may not be discovered with eddy current in ferrite materials.
The system presented herein was realized entirely using phased-array technology. Compared to conventional ultrasonic probes, phased array transducers bear in particular two advantages within the context of this application:

1. By varying the electronic focus, it is possible to use one probe for the complete diameter range. Variations in reference defect response, which can be attributed to the different curvature radius of the material and the different depths of the reference defects, can be compensated by adjusting the electronic focus, optimizing the sensitivity.

2. Phased-array transducers operate with so-called virtual probes, i.e. a subset of elements shot simultaneously with appropriate delay-laws, which represent one conventional transducer with equivalent properties. Due to the small element size and the ability, to vary the position two virtual probes in steps as small as the difference between two elements, a high degree of overlapping can be achieved. This is in particular important if small defects shall be detected. Figure 7 illustrates a simple example of the effect of overlapping.

In summary, phased array probes allow on the one hand a strong overlapping. On the other hand, the helix pitch can be kept at a comparably large value due to the overall length of the phased array probe, maintaining the throughput constraints. The area between the helix tracks is highly resolved by the strongly overlapping virtual probes.

<table>
<thead>
<tr>
<th>No overlap</th>
<th>66% overlap</th>
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<td><img src="image" alt="Figure 7: Effect of virtual probe overlapping" /></td>
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Figure 7: Effect of virtual probe overlapping
3. Automated Inspection Concept

3.1 Static Results

Calibration standards have been manufactured for several diameters along the diameter range, starting at 76mm up to 387mm. As an example, that static results from a 317mm billet are included in Figure 8.

![Figure 8: Static defects in 317mm pipe, Compression wave in perpendicular arrangement](image)

The variations in sensitivity are compensated by appropriate TCG curves. Figure 9 shows the response from the longitudinal notches.

![Figure 9: Signals from notches, shear wave in angular arrangement (45°)](image)

3.2 Dynamic Results

Dynamic tests are carried out with respect to the flat bottom holes. Contrary to common inspections within automotive fields, it is not possible to assume a given defect length in axial direction, typically in the range of ½”-1” (12.7mm - 25.4mm), which would allow to test axially with increased shot distances. The result is that the calibration test bars can be used for dynamic tests as well. Two kinds of data representation are recorded:

1. Analog charts with 10mm resolution in axial direction
2. C-Scans in Amplitude and TOF with resolution to 1mm.

Apart from that, overviews and statistics pages are recorded in addition. All test data are stored in single bar files and can be processed offline.

![Analog Chart for core defects, bar with natural defects](image1)

![C-Scan near surface defects Reference Bar D=115mm](image2)

Figure 10: Dynamic Test

Depending on the defect size, the Test Setup in the machine can be altered in order to allow a higher speed. This operation is based on the possibility of larger shot distances when larger defects shall be detected.

4. Manual Inspection Concept

4.1 Principle

After the automatic eddy current testing / ultrasonic phased-array testing, occurs a manual re-inspection of the marked defect areas as well as of the untested ends.

4.2 Visual Testing

The untested ends, as well as the marked defect areas over the circumference of the eddy current testing, is cleaned and followed by a visual surface inspection. The type, length and the depth of the defect is determined. Under consideration of the type of product (billet or bar) the decision of the following proceeding is taken. Usually a grinding operation within ¾ of the machining tolerance of the customer respectively within the dimension tolerance is allowed. Unacceptable defects lead to rejection of the bar or section of the bar.

4.2 Ultrasonic Testing

The untested ends, as well as the marked defect areas over the circumference of the automatic ultrasonic phased-array testing (+100 mm left and right), is cleaned and followed by a manual ultrasonic straight beam inspection (pulse-echo-method / contact technique). The sensitivity adjustment is done by using the DAC method with the same reference defects which are used by the automatic ultrasonic phased-array testing. The elongation of the unacceptable defect areas is marked on the bar and lead, under consideration of the ordered lengths, to rejection of the bar or section of the bar.