EVOLUTION OF THE ULTRASONIC INSPECTION OF HEAVY ROTOR FORGINGS OVER THE LAST DECADES

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ABSTRACT. All types of heavy forgings that are used in energy machine industry, rotor shafts as well as discs, retaining rings or tie bolts are subject to extensive nondestructive inspections before they are delivered to the customer. Due to the availability of the parts in simple shapes, these forgings are very well suited for full volmetric inspections using ultrasound. In the beginning, these inspections were carried out manually, using straight beam probes and analogue equipment. Higher requirements in reliability, efficiency, safety and power output in the machines have lead to higher requirements for the ultrasonic inspection in the form of more scanning directions, higher sensitivity demands and improved documentation means. This and the increasing use of high alloy materials for ever growing parts, increase the need for more and more sophisticated methods for testing the forgings. Angle scans and sizing technologies like DGS have been implemented, and for more than 15 years now, mechanized and automated inspections have gained importance since they allow better documentation as well as easier evaluation of the recorded data using different views (B- C- or D-Scans), projections or tomography views. The latest major development has been the availability of phased array probes to increase the flexibility of the inspection systems. Many results of the ongoing research in ultrasonic's have not been implemented yet. Today's availability of fast computers, large and fast data storages allows saving RF inspection data and applying sophisticated signal processing methods. For example linear diffraction tomography methods like SAFT offer tools for 3D reconstruction of inspection data, simplifying sizing and locating of defects as well as for improving signal to noise ratios. While such methods are already applied in medical ultrasonic's, they are still to be implemented in the steel industry. This paper describes the development of the ultrasonic inspection of heavy forgings from the beginning up to today at the example of Saarschmiede GmbH explains the difficulties in implementing changes and gives an outlook over the current progression.

Keywords: History, Ultrasonic, UT, Forging, Turbine, Application
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INTRODUCTION

Saarschmiede has been one of the prime suppliers of heavy forgings for energy machinery as well as general machinery and the aerospace industry for more than 50 years now. In the context of ever higher degrees of sophistication of the machinery, it is of continuously growing importance, for manufacturers and suppliers alike, to ensure the ever growing demands in the quality of the parts by reliable and sufficiently sensitive inspection systems. Due to the relatively

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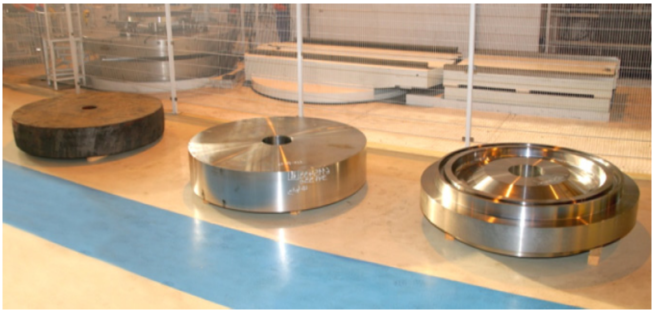

FIGURE 1. Disc Forgings in different production stages (from left to right): after quality heat treatment, UT shape, delivery shape.

simple geometry of parts like generator and turbine shafts, turbine discs, retaining rings as well as missile booster cases, containment vessels and tubes, and their large dimensions which amount up to 20m in length and 4m in diameter, the method of choice for a volumetric inspection for heavy forgings is obviously ultrasonic testing.

Besides the simple shapes it is their good surface condition as well, that makes forgings ideal candidates for ultrasonic inspections. Figure 1 shows disc forgings in three different production steps: the first is after quality heat treatment, with a rough surface which is not suitable for UT inspections. Thus the forging is machined into a shape that allows a 100% inspection coverage of the final part with flat and smooth surfaces, and finally the delivery shape. Still the nondestructive testing has to solve some difficult challenges: due to the part size the soundpaths are extremely long, the sensitivity requirements given by the customers are very high and the parts are difficult to handle due to their weight, which is often larger than 100t.

The Past

When Saarschmiede, at this time still part of the “Stahlwerke Röchling Burbach”, entered the market of large energy machines by building a hydraulic 1500t press in 1966, all basic knowledge and equipment necessary to perform ultrasonic inspections on rotor forgings were already available. The method of choice was the ultrasonic impulse-echo method since transmission experiments carry less information and are difficult to perform for large parts. Suppliers of devices were mainly Krautkrämer (e.g. USIP-10W), Karl Deutsch and Siemens, the devices were driven by selected tubes, they were heavy and their mobility was limited. In contrast to castings, which have a relatively coarse grain structure and thus require low frequency inspection with 0.1Mhz to 1MHz, the probes applied to fine-grained forgings in their final inspection were 24mm single-crystal piezoelectric probes with a center frequency of 2MHz. Most of the inspection effort was done as radial straight beam inspections since the extend of most of the possible defects like inclusions and cracks is oriented parallel to the grain structure produced by the forging process, and the defects have the highest reflectivity if the ultrasonic beam hit them in a normal incidence. Axial straight beam inspections were performed as well from the end faces of the components. As coupling medium generally oil was used. All inspections were strictly performed manually; figure 2 shows pictures of early manual UT inspections carried out in the forging shop, indicating quite rough inspection conditions.

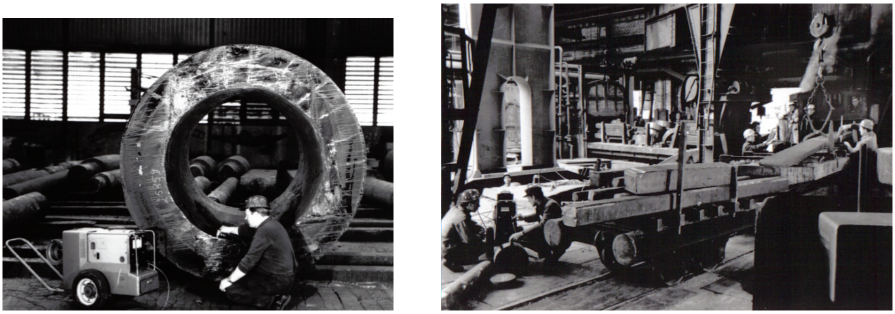

FIGURE 2. Manual ultrasonic inspections in the forging shop in the past [6].

Due to the high value and the high production cost of the components, a mere detection of defects has not been sufficient, but a detailed qualitative and quantitative description and classification of indications was required as information input to the customer's material and design engineering to determine the usability of the parts. Simple sizing methods, based on transducer travel, can only be applied to defects larger than the used transducer's beam diameter; the defects to be assessed in forgings are much smaller than the beam diameters even of focused probes though. Two alternative sizing methods, based on amplitude, are applied since the early 1960s. For the first method calibration reflectors, usually notches or flat bottom holes (FBH), are brought into the component (direct method) or into calibration blocks (indirect method) and the amplitude of indications is compared to the echo amplitude of the calibration reflectors, taking into account necessary correction values. For the second method, which is used mainly in Europe, calibration is done on the backwall of the component, and the echo amplitude of indications is compared to theoretically computed amplitude diagrams published by J. Krautkrämer in 1959. These diagrams compare the reflectivity of FBH with respect to distance, gain and size and are thus called DGS diagrams (german: AVG, Amplitude Verstärkung Größe) [3]. The diagrams are computed monochromatically and are only valid for narrowband transducers. However, both amplitude based methods do only compare the reflectivity of defects with the reflectivity of ideal reflectors (usually FBH) and do not account for structure, real form and orientation of defects.

The assessment of indications, which are possible defects, is difficult to perform though from A-Scans, a lot of computation and sketching is necessary. Attempts to find ways for better and more detailed descriptions of indications were already performed before 1960: at

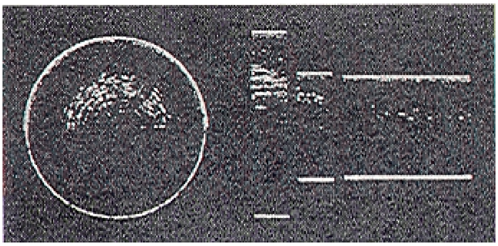

FIGURE 3. First B-Scan of a turbine rotor forging, Michalski, 1956.

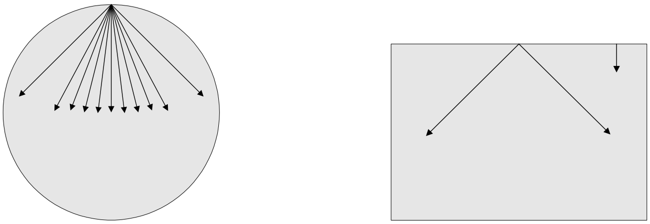

FIGURE 4. Radial tangential scans and axial scans with angle beams.

Saarschmiede Dr.Michalski recorded the first B-scan of a turbine forging using optical devices. The application of sophisticated methods for displaying ultrasonic images and image processing was not established before the general availability of computers with large computation power. Angle beam probes with fixed angles (45°, 37°) were available and used early, the application of multiple beam angles using plexigalss wedges only started after a rotor failure in 1988. Due to the off-centered placement of a defect it was undersized, leading to the complete failure of the part [5,8,9]. As a consequence the radial inspection was extended by eight additional scans, typically using 7°, 14°, 21° and 28° beam angles (for a probe with a -6dB beamspread of 3.5°) in both directions, so an off centered or angled indication would be undersized by not more than 6 dB. Moreover, once an indication is found, angles in-between have to be used for the best possible sizing of the indication by maximizing the amplitude response. Up to today, many specifications for ultrasonic inspections of rotor forgings still require plexiglass wedges to obtain exactly these beam angles.

While so far all inspections were almost exclusively performed manually using hand-heldmobile equipment, the increase in requirement of the machinery also called for an increase in the quality requirements of the forgings. To fulfill these more complex inspection procedures and higher registration sensitivity requirements, mechanized and automated inspection facilities were build. Here, automated inspection means that the component as well as the search unit is moved by a computer controlled manipulator and their positions are tracked and recorded, and that the complete data acquisition is done with a computer based system storing all the data. These facilities overcome the disadvantages of classical manual inspections: varying scanning velocities, inaccurate overlapping of scanning passes, loss of operator attentiveness on watching the instrument screen, monotony of repetitive motion patterns, physical fatigue and of course the repetitive inspections. Besides a reduced inspection time, they allow for reproducible inspections and an improved documentation and thus to improved acceptance procedures. They are also the basis for all kinds of image-producing methods and also simplify the data evaluation a lot.

The first automated inspection system build at Saarschmiede in 1978 was an immersion system for the inspection of rotational parts. It was based on a Krautkrämer KS3000 UT system and later changed to USI I systems, both driven by selected tubes. This system was originally build to satisfy requirements from the aerospace industry and was replaced in 1984 by a system based on a Krautkrämer USDI ultrasonic device and a Z80 based computer that still used an analogue display but already allowed digital storage of the data in EEPROMs and magnetic bubble memory. All UT systems were exchanged against fully digitalized systems in 1994.

FIGURE 5. Classic disc inspection facility 1 (left) and modern disc inspection system (right).

In 1993 the first mechanized inspection facility for rotor shafts (based on a Krautkrämer USIP 11) was build, one year later the automated General Electric Solid Rotor Systems followed. It allowed quick and easy B-scan display for the first time. Both shaft inspection systems still used oil as coupling medium. Figure 5 shows (on the left) the first automated inspection facility build or disc-type forgings in 1995 by IRT and Vogt Werkstoffprüfsysteme, applying a ScanMaster LFS300 UT system. The 3-point-roller system with lateral anti-drift rolls supports components of up to 40 tons of weight, 3200 mm diameter and 3000 mm height and the system is typically used to inspect discs, shaft ends and due to its 3-axis manipulator also cylindrical and dome-shaped missile booster case components. The inspection is still done in a single-channel mode, so for each scan position a complete scan has to be set up. Due to the growing importance of environmental protection oil could not used as coupling medium any more, and this was the first system that uses a water gap for coupling, all systems build after 1995 use water coupling as well.

Due to the continuously growing demand for automated inspections, additional shaft and disc inspection facilities were built in 1998 and 2002.

The Present

Currently Saarschmiede operates 12 automated inspection facilities: six for disc-type forgings, two for large rotor shafts, an immersion system for bars, an immersion system for rotational parts and two immersion systems for retaining rings. The largest currently operating disc inspection facilities is a twin facility build in 2006 that can carry components with a maximum height of 3500 mm, a maximum diameter of 3000 mm and a maximum weight of 65 tons. They are equipped with the Areva IntelligeNDT Systems & Services Saphir^{Plus} ultrasonic system that offers 64 channels, currently there are two more facilities under construction that will be able to test even larger and heavier parts using up to 128 channels. The newest shaft inspection facility No. 2 (shown in Figure 6), constructed in 2007, is also equipped with the IntelligeNDT Systems & Services Saphir^{Plus} ultrasonic system with 64 channels. It can inspect components from 1500 mm length up to 15000 mm length, with a weight up to 100 tons.

FIGURE 6. Shaft inspection facility (2007) and six unit probe holder.

The transition from the classical ultrasonic inspection facilities can be seen in the year 2002, when phased array systems were introduced. The modern UT systems offer multi-channel inspections that allow the use of three 16-element phased array probes and 16 conventional probes at once. Using specially designed probe holders that carry three (discs) or up to six probes (shafts) at once allow significant reduction the inspection and setup times. The basic principle of phased array was already proposed in the late 60's; the first system available in Germany was built in 1980 by the Fraunhofer Institute for NDE [6]. It took these systems more than 20 years though, to mature to industrial application, and due to the lack of norms, standards and experience they are still used only for a limited number of customers. Each system build is tested and qualified by each customer, to a procedure given by the customer. Most inspection specifications are still focusing on conventional ultrasound, so specific inspection procedures must be written for each component that is inspected using the new technique.

In addition to the multi-channel inspections the new facilities are based on modern and fast computers and offer sophisticated tools for data storage and evaluation: the data can be visualized in different images (B-scans, C-scans, D-scans, projections and tomographies), data cursors can be used to assess and measure defect positions and size (in geometry and amplitude) and images can be used for better documentation. Data can be stored in different ways, full RF-data can be recorded, but data compression algorithms (e.g. ALOK) are available to keep the amount of collected data small enough to handle.

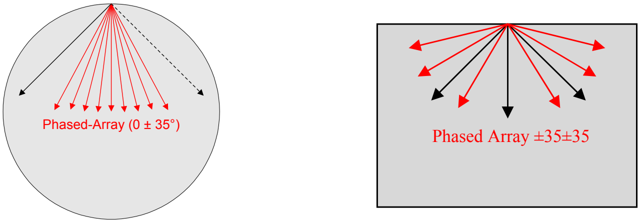

FIGURE 7. Scan Positions using phased array probes.

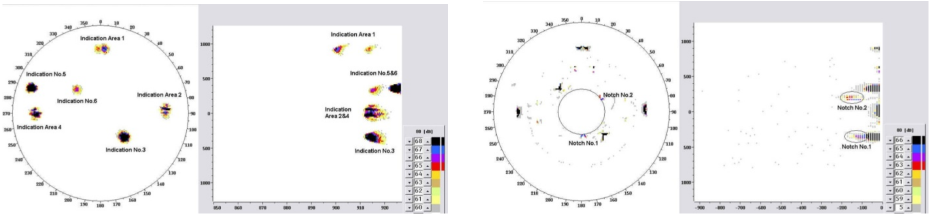

FIGURE 8. Results of a radial and a axial inspection of the test disc: tomography and projection view.

In spite of the high capacity for automated inspection the manual inspection is still performed, mainly for customers who do not allow automated scans in their NDT specifications. The basic principle for manual UT has not changed, the devices have become easier to handle though, and they are more mobile nowadays and carry many sophisticated tools to simply calibration and defect assessment. Coupling is done using gel.

THE FUTURE – OUTLOOK

Throughout the last 60 years science has delivered progress in many fields that has not found its way into application yet. The main methods that have potential for application in the future can be divided into two types: modeling and imaging.

Many different methods have been presented up to today; some of them show good options to find their way into the application of the inspection of heavy forgings. Main aim for modeling in this case will be the better understanding of the basic principles of ultrasound and an improvement of the education. Modeling will also strongly improve the knowledge about the sound field of the applied probes and simplify the design of new probes. For this task, methods have to be selected that allow fast computation of large volumes, taking into account as many wave phenomena as possible.

Imaging is already in use as far as the display of A, B, C, and D-Scans, and even of tomographies. Throughout the last 40 years methods have been developed that allow the three-dimensional imaging of the inspected volume using mathematical algorithms. One of these methods - SAFT (Synthetic Aperture Focusing Technique) – a linear three-dimensional imaging method, has been showing great potential to improve the assessment and documentation of indications. With the availability of fast computers as well as large and cheap data storage the application of this method in 3D has become possible, even for large components. The implementation of this method – or one of its derivatives like FT-SAFT- is going to be the task for the coming years.

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