



Investigations to Introduce the Probability of Detection Method for Ultrasonic Inspection of Hollow Axles at Deutsche Bahn

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Abstract. Currently at Deutsche Bahn (DB) ultrasonic inspections in maintenance procedures for wheelset axles with a bore hole are, to the greatest possible extent, carried out using automated ultrasonic inspection system. Although the acceptance levels are in accordance with DIN 27201 part 7, the testing results have shown in recent years that in the case of true indications, the effective defect sizes were far below the level of acceptance. Due to this experience it can be assumed that the automated ultrasonic inspection systems are testing substantially more sensitively than required. This increased sensitivity leads to an increase in false indications, generally resulting in the unnecessary demounting of wheelsets.

In research cooperation between Federal Institute for Materials Research and Testing (BAM) and DB the effective flaw detection sensitivity of existing automated ultrasonic inspection system will be determined and the true/false indication ratio optimised. Through systematic investigations with the Probability of Detection method on the existing automated ultrasonic inspection system the results could be directly applied to the optimisation of existing ultrasonic inspections of wheelset axles with a bore hole in maintenance procedures and the level of reliability can be considerably increased.



1. Introduction

The experiences of the last years have shown that automated ultrasonic inspection systems for wheelset axels with a bore hole (HPS) are able to detect even smaller defects than required. The outcomes of this observation arouse two questions:

How can the increase in detection sensitivity be used for the maintenance procedure and is the smallest detected defect the correct indicator for the reliability of an inspection system? For safety reasons the second question has to be answered with priority. For the characterisation of the reliability of a non-destructive testing system the largest defect that can be missed is more important than the smallest defect that can be detected.

For the determination of the probability of detecting defects, and the optimisation of the true/false indication ratio, the implementation of the Probability of Detection (POD) - methodology has proven to be appropriate in other industrial sectors, MÜLLER [1]. The objective now is to extend the POD- methodology for ultrasonic inspections at DB.

In order to grasp the focal point of the research cooperation and the need to introduce a new method, an understanding about the current inspection process is fundamental.

1.1 Relevant technical regulations

The German industrial standard DIN 27 201 T7 [2] is applicable for sensitivity settings. An acceptance level for ultrasonic testing equal to a saw-cut of 2 mm in depth and an additional safety margin of 6 dB is recommended by the standard.

1.2 Sensitivity setting for HPS systems according to DIN 27 201 T7

In order to achieve the required level of acceptance uniformly along the whole axle length, the registration level is modified depending on the axial position. This is to consider the influence of different diameters and of diameter transitions. The modification in the registration level is done by flaw gates with different heights. The positions of the flaw gates in the time domain are also shifted to guarantee the echo expectance range and to eliminate echoes caused by the axle geometry. Especially in the areas where the axle tapers or widens a large number of flaw gates are needed to eliminate echoes caused by the axle geometry. For adjusting the heights and the position of the flaw gates, reference axles are used. A simplified sketch of a reference axle is shown in **Fig. 1. (a)**. The saw-cuts are placed in each of the diameters and diameter transitions of the axle.

For the sensitivity setting, the amplitude of the reflections for all saw-cuts is estimated for the different probes.

The registration level is set to half of the amplitude (-6 dB) of the saw-cut reflection as shown in **Fig. 1. (b)**.

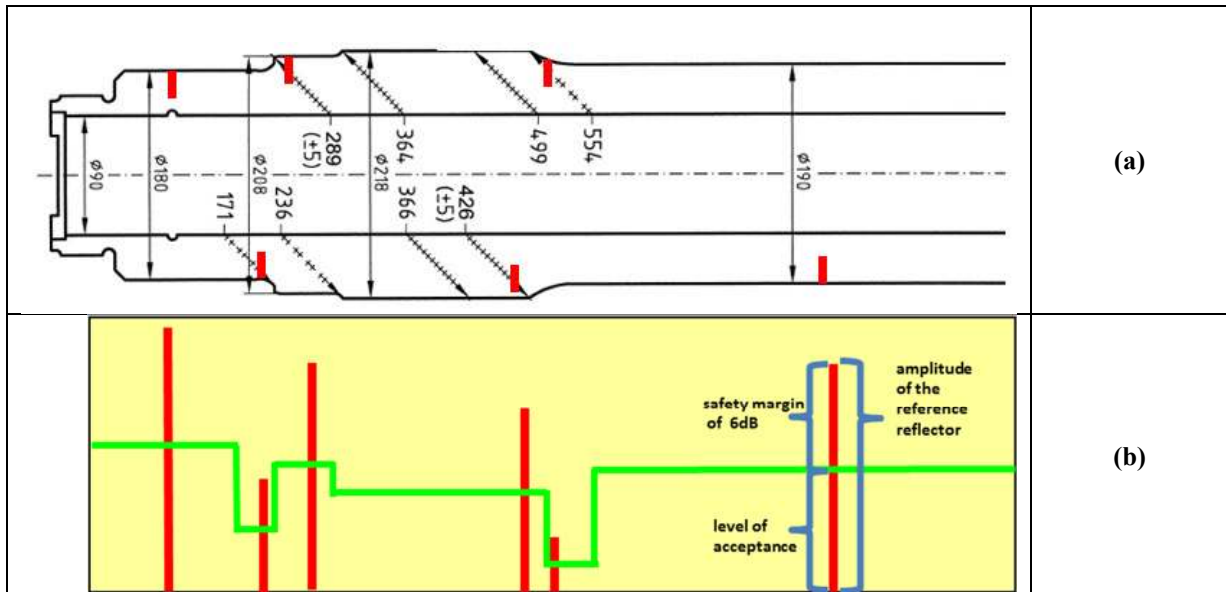


Fig. 1. Simplified sketches of a reference axle with 2 mm saw-cut reference reflectors (red) (a) and changing heights of the level of acceptance (green line) (b). The amplitudes of the reference reflector reflections (red bars) are twice as high as the registration level in every section due to a safety margin of 6 dB. For a general demonstration of the adjustments, the sketches are simplified since not all notches and changes in levels of acceptance are displayed.

1.3 Technique of the automated ultrasonic inspection systems for wheelset axels with a bore hole (HPS)

Automated ultrasonic inspection systems, so called HPS, are used for the inspection of wheelset axles with a bore hole at Deutsche Bahn (DB). The most widely used HPS type with nearly 100 systems at DB and further systems in Austria, Switzerland, Russia, Great Britain and South Korea is described in the following paper. These systems are able to scan one axle within 12 minutes. The probe head is equipped with 10 normal beam probes, arranged as shown in **Fig. 2**. The ultrasound is induced via an oil path into the axle. The dark and light coloured green probes are for the detection of longitudinal defects on the outer surface and the blue coloured probes for internal defects, the green and blue probes are working in double transducer mode. The red and yellow coloured probes are used for the detection of circumferential defects at the outer surface of the axle. The red and yellow probes are working in transducer mode and have a beam angle of 35° and 70° . Every colour of transducer represents a so called testing function. The circumferential defects are the most critical ones and therefore the focus of this research.

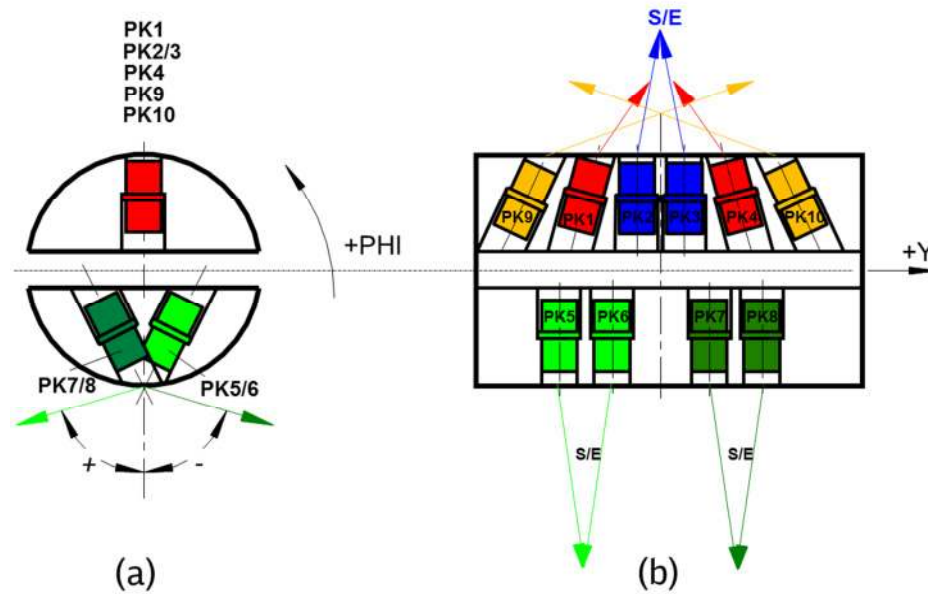


Fig. 2. Arrangement of probe head. Lateral (a) and longitudinal (b) cross section. Red and yellow probes for detection of circumferential defects and green probes for longitudinal defects in the outside surface. Blue probes for detection of internal defects.

As explained in the paragraph on the sensitivity setting, the modification of the registration level has to be adjusted for the different sections of the axle and for every testing function in a section.

1.4 Defect shapes

In Germany the saw-cut is the traditional reference reflector for wheelset axles with a bore hole. The advantages of this reference reflector lie in its repeatable and cost efficient method of production. The saw-cut is used both for automated testing as well as for manual testing.

In fracture mechanics a different crack shape is used. The remaining lifetime is calculated with a crack of a semi-elliptical shape and an a/c ratio of 0.8, where a represents the depth extension of the crack and c represents one half of the crack length at the surface.

This assumption of the crack shape in the remaining lifetime calculation corresponds to the actually reported fatigue crack shape.

In **Fig. 3.** a circumferential fatigue crack with a depth of $a = 0.75$ mm and a length of $2c = 1.9$ mm is shown. This crack was detected during an ultrasonic inspection using a HPS. The crack has an a/c ratio of 0.79.

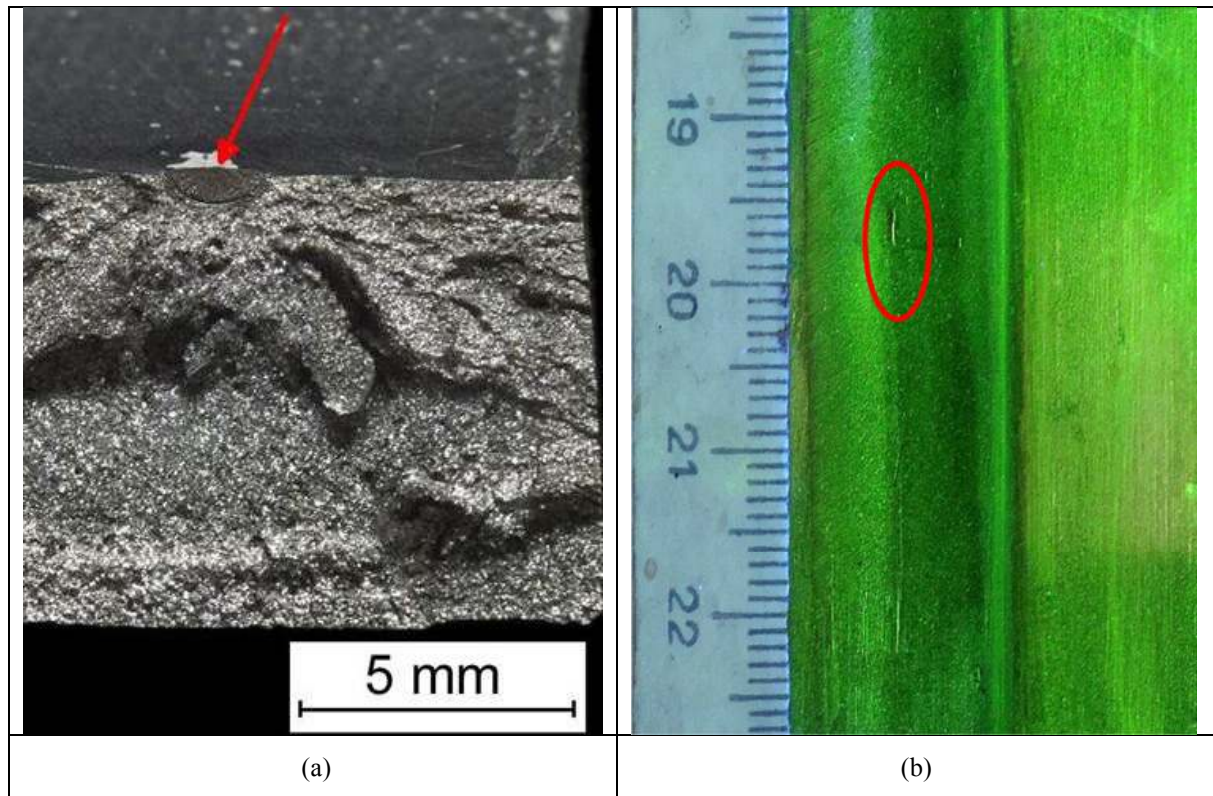


Fig. 3. Photo of a fracture surface after crack-opening of a circumferential crack (marked with a red arrow) detected during inspection using HPS (a). Crack with a depth of $a = 0.75$ mm and a length of $2c = 1.9$ mm. Magnetic particle testing indication before crack-opening (b).

A typical crack is shown in **Fig. 4.** MÄDLER [4], developed during a full scale test for determining the residual lifetimes of wheelset axles. In this test the development of the crack growth was observed in dependency of the load spectrum with changing amplitudes. The propagation of the lines of rest during crack growth are visible, and the a/c ratio can be estimated over the crack growth. This crack was initiated by a spark-eroded notch, and has a depth of 1.2 mm and an a/c ratio of 0.8. With the propagation of the crack, the a/c ratio decreases. In this example, the a/c ratio declines to 0.54 for the 13.5 mm deep crack. Around 2 mm crack depth extension the a/c ratio is approximately in the range of 0.8.

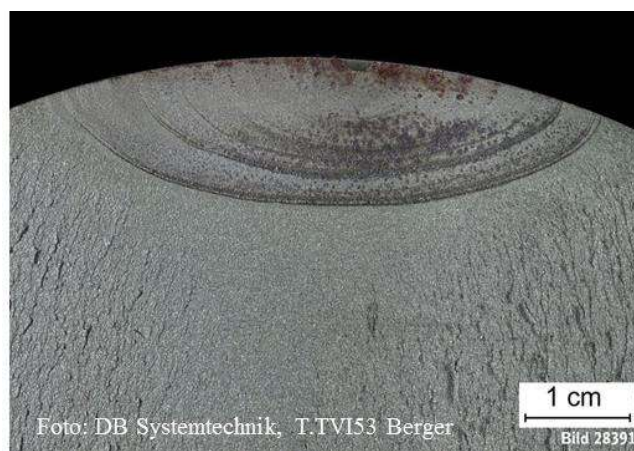


Fig. 4. Photo of fracture surface after crack-opening MÄDLER [4]. The crack was developed in the course of a full scale Test. The lines of rest are visible.

Different kinds of shapes were introduced. The fracture mechanical shape fits to the shape of detected and initiated fatigue cracks. As reported by CARBONI [5] and

PAVLOVIC [6] the defect shape strongly affects the POD. For the estimation of the reliability of a testing system the defect shape ought to be taken into account.

2. Scope and planning of experiments

2.1 Objectives of the investigations

Based on the requirements explained in the introduction, the following objectives were specified as the focal points of the investigation:

As shown in paragraph 1.4 there is a difference between the traditional ultrasonic reference reflector and fatigue cracks observed. CARBONI [5] has noted that the reflecting area has to be taken into account rather than the depth extension of the reflector. PAVLOVIC [6] explored the influence of the depth extension to length ratio to the POD as well. It is essential to carry out the POD investigation on real fatigue cracks or comparable flaws precisely because real fatigue cracks have to be detected in ultrasonic inspection. A set of axels will be produced with fatigue cracks graded by size. Due to their expense, only a limited number of axles with fatigue cracks will be produced. To ensure that the defect sizes are in the relevant range, experiments will primarily be conducted in combination with simulation studies.

As discussed in paragraph 1.2 the axle geometry and failure location has an influence on the POD. The POD has to be determined for different diameters and transitions. For this reason, POD measurements have to be carried out at different positions. To support and model the measurements between the measuring points, CIVA simulation will be used (CIVA 2015 (11.1)). An artificial reference reflector, which is comparable to fatigue cracks, is necessary because they are too costly to produce themselves. If a lower level of acceptance is possible in the maintenance procedure, a reference reflector is needed for the sensitivity settings of the HPS systems. The reference reflector should be similar to the real cracks so that the results of the POD investigations can be transferred to the maintenance procedure. Furthermore, the reference reflector should be repeatable and cost efficient to produce. An extensive amount of reference reflectors is needed. In a single reference axle there can be more than 20 reference reflectors depending on the axle geometry, and each HPS needs one reference axle for each tested bore diameter. It was shown in paragraph 1.3 that the HPS system tests with probes of different directions and angles simultaneously. The parallel use of several so called testing functions has an influence that must be accounted for in the POD.

2.2 Comparison of saw-cut and reflector with a/c ratio of 0.8

In order to support the experimental design, simulations are carried out to focus the experiments on the relevant topics. As mentioned before, the shape of the reflector is important a reference reflector with an a/c ratio of 0.8 was compared with the saw-cut for different reflector depths by means of CIVA simulations. In Fig. 5, the reflection amplitude for the saw-cut (continuous line) and the reflector with an a/c ratio 0.8 are shown in dB over the reflector depth extension in mm for different axle diameters.

It can be observed that the amplitudes at 2 mm reflector depth extension are nearly identical for both reflector types. With decreasing depth extension of the reflectors the reflector with an a/c ratio of 0.8 declines more intensely than the saw-cut. The difference for a depth extension of 1 mm is about 5 dB and for 0.5 mm depth extension 10 dB. The slope for the reflection by the saw-cut at decreasing reflector depth extension is constant,

up to a slight drop for depth extensions less than 1 mm. For the semi-elliptical reflector the slope decreases continuously.

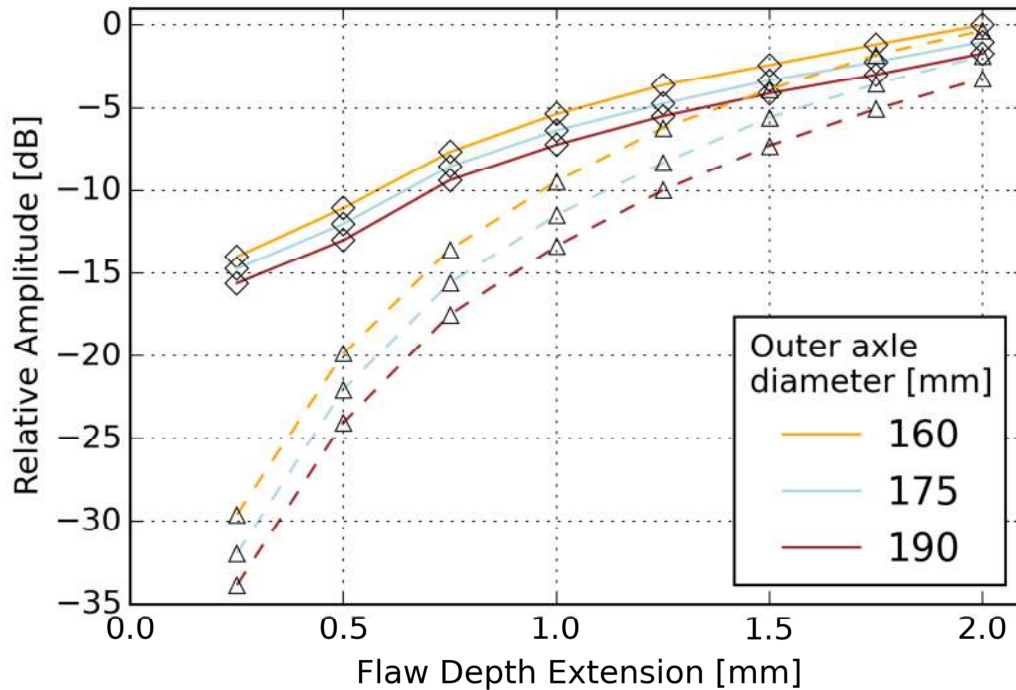


Fig. 5. CIVA simulation of amplitude in dB over the reflector depth extension in mm for the saw-cut (continuous lines) and the semi-elliptical reflector with an a/c ratio of 0.8 (dashed line) for different axle diameters. The bore has a constant diameter of 65 mm

In terms of POD investigations, this means that due to the different behaviours of the amplitude and for a reflector depth extension below 2 mm a saw-cut is not appropriate for using POD because the saw cut yields much higher amplitudes for smaller defects than the real cracks.

3. Conclusions

As shown in paragraph 1.1, a reflector depth extension of 2 mm and an overall safety margin of 6 dB are recommended by the standard DIN 27210 T7 to ensure a level of acceptance of 2 mm [2].

Today, as a result of advances in the development of automated ultrasonic testing systems, it is possible to conduct more sensitive tests. The scope of the above mentioned standard does not include the estimation of the actual performance of a testing system and evaluation for flaws smaller than 2 mm. Moreover, the overall safety margin of 6 dB leads to an increased sensitivity and, for this reason, to an increase of false indications. In contrast to the overall safety margin, the POD-Method gives a defect size which will be detected with high probability and in this way providing a defined safety level for a specific testing system. It is concluded that more parameters aside from the crack depth must be considered (such as the crack shape or location of the defect), and the POD investigations have to be extended to a multiparameter approach.

4. References

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