# Ultrasonic Testing during Production - Semi Finished-Product or Component Testing

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Dr.(USA) Wolfram A. Karl Deutsch, Dr.-Ing. Volker Schuster, Hans-Jörgen Andersen

KARL DEUTSCH Pruef- und Messgeraetebau GmbH + Co KG, Wuppertal

Tel: (+49-202) 7192 - 0, Fax: (+49-202) 714 - 932, info@karldeutsch.de, www.karldeutsch.de

Jo Chielens

CHIELENS BVBA, Adelaarstraat 8, 9051 Gent, Belgium

Phone: (+32-9) 222-2260, Fax: (+32-9) 222-6048, chielens.bvba@pandora.be

Mariano Baroni, Dino de Toni

ECOMAG SRL, Via F.lli Bressan 21, 20126 Milano, Italy

Phone: (+39-02) 2700-0665, Fax: (+39-02) 2700-0902, info@ecomagsrl.it, www.ecomagsrl.it

## Introduction

Ultrasonic testing plays an important role during the production of high-quality or safety-relevant products. Depending on the requirements and the final component, many testing concepts and setups are in use. During the early stage of production an initial ultrasonic test is often applied for the semi finished products (billets, bars, tubes etc.). This ensures that further production steps are only carried out with appropriate material.

In many cases, another inspection of the finished component (or during an intermediate production step) is applied. More focus can then be spent on the known critical areas of the component. Machined surfaces usually allow for the detection of smaller defects sizes. In this case however, longer testing times per volume of tested material might be required for proper results.

Some typical practical examples for ultrasonic testing set-ups are presented in this paper. Usually the test equipment is stationary and its features are dependent on the product to be tested, the test specifications and the desired throughput. Also the cost of a nondestructive test is an important factor, even though the safety of the final product should be the most important issue.

One key feature of every automated testing system are the ultrasonic probes. The physical properties of the probes have to be well during controlled during their production. The change of a probe should not affect the overall performance of the testing system and its sensitivity. This paper presents one example where the sound beam geometry was optimised for high coverage per probe.

For the inspection of semi finished products the evaluation of the ultrasonic signals is carried out with multi-channel electronics. The electronics can be programmed for the inspection of types of products such as bars, tubes etc. In most cases, many ultrasonic channels are necessary. The signals from all channels are processed in real-time. Each channel is equipped with four gates and with up to three thresholds. A fast programmable time-corrected gain (TCG) is implemented which compensates the acoustic damping for increasing travel time. The result is a very even testing sensitivity. All mentioned parameters can be individually configured for each testing channel.

For component testing with small number of channels, a simple solution for the ultrasonic electronics might be sufficient. A fast portable ultrasonic flaw detector might fulfil the testing task. Typical requirements include a high pulse repetition frequency (1-4 kHz), interface echo trigger for immersion testing to couple the flaw gate to the surface position, fast amplitude evaluation and supervision of the back wall echo for coupling check.

## Coupling for Automated Ultrasonic Testing

Most industrial applications make use of water as a coupling medium. Automated testing often requires high relative speeds between the surface of the product and the ultrasonic probe(s). At the same time little mechanical wear and stable coupling conditions have to be achieved.

Component testing often uses an immersion tank where piece by piece inspection is carried out. Immersion testing has also been adapted for the inspection of long products (bars, tubes). A specially designed water chamber has openings on entry and exit side. The probes are mechanically mounted to probe holders within the water tank. Stationary probes, rotating probes or array probes can be used in such a setup.

Water jet coupling makes use of a laminar water jet which guides the sound beam onto the specimen surface. The water jet diameter must be larger than the sound beam diameter to avoid acoustical distortions. The water nozzle within the probe holder must ensure a laminar flow. The probe holder rests on the specimen with skids or rollers. Since the distance between probe and specimen surface is in the order of several centimetres, the probe itself is well protected.

Large specimens can be inspected in partial immersion. Bars and tubes are often transported with a helical conveyor. The probes are mounted into an immersion tank below the specimen.

Water gap coupling requires only little water and requires a narrow gap between probe and specimen surface, typically 0.5 mm. The probe holder rests on the specimen surface with shoes or rollers. A curved specimen (tube, bar) might require curved shoes which is a drawback of this technique. Also the small gap endangers the probe, especially if black products are tested. Advantages of this technique are the possibility to use large probes and to use dual-element probes. Therefore strip testing is a typical application where small dead zones are important and large coverage per channel is needed. The last mentioned techniques all offer the advantage that the probes are mechanically guided along the specimen surface to compensate for geometrical tolerances or position deviations during transport.

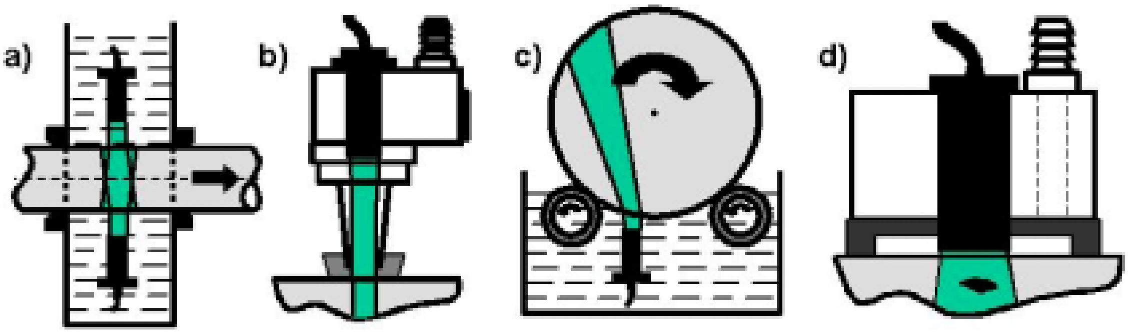


**Figure Ultrasonic Coupling. a)** immersion testing adapted for bars and tubes, **b)** contact-free water jet coupling, **c)** partial immersion for long products such as bars and tubes, and **d)** water gap coupling.

## Ultrasonic Testing of Quadratic and Round Billets

The first ultrasonic test is often applied in a very early stage of steel production. Billets are used as input product for many components. State-of-the-art of billet production uses continuous casting, leading to the consequence that defects can occur in the entire cross section. Billets from casted ingots require a core-defect detection only, because shrinking within the ingot affects mostly the centre portion.

Typically, several rolling stands reduce the diameter little by little and form a material structure which is possible to be tested with ultrasound. The finer the grain structure, the better the chances to detect small defects. The maximum billet dimensions during the initial ultrasonic test are typically around 200 mm.

Modern ultrasonic testing systems are capable to detect defect sizes of 1.5-3 mm flat bottom hole. The testing speed is in the order of 1 m/sec and the billets are transported with V-rollers. The straightness tolerances, especially at the billet ends, require that the probe carriers are moveable between the safety and the testing position. Light barriers detect the billet position and position encoders which are connected to the roller conveyor monitor the current testing speed. After the billet enters the testing system, the probe carriers are pneumatically moved into the test position. Short untested ends are an important criterion for selecting a proper testing unit. Therefore, fast probe positioning and precise position monitoring is mandatory.

Wear and contact free coupling is achieved with guided water jets. Highly-sensitive piezo-composite immersion probes with round housing are mounted into compact multi-probe holders. Up to four probe holders can be used to inspect the quadratic billets from all four sides. Since the dead zone of the back wall echo is smaller than the dead zone of the interface echo, testing from all four sides is advantageous but also a matter of cost. The total number of probes depends on the billet diameter and the required coverage of the cross section. The example system shown below contains 28 probes distributed over four probe holders.

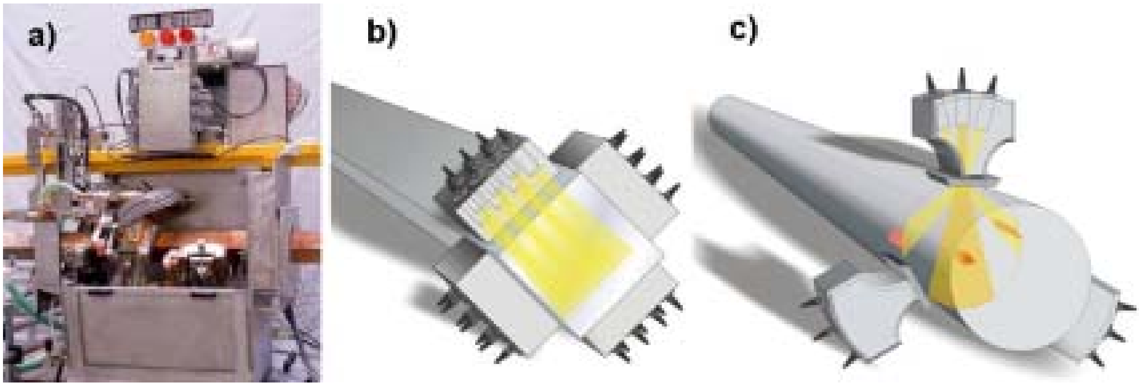


**Figure Billet Testing. a)** mechanics of billet testing system, **b)** testing principle for quadratic billets, **c)** testing principle for round billets.

## Special Probes for Automated Ultrasonic Testing – Example Billet Testing

Automated ultrasonic testing requires best-possible coverage of the specimen, preferably with a small number of channels and a high testing sensitivity. Since those requirements contradict each other, a practical compromise has to be found. The ultrasonic probes are one key-feature of every testing system. Sound beam focussing or defocusing, the proper choice of the piezoelectric material and the testing frequency are relevant parameters. In addition, probes for automated ultrasonic testing have to be highly sensitive and meet the strict requirements of DIN EN ISO 12668-2. A change of probes should not affect the performance of the testing system and therefore strict quality control shall ensure small tolerances during the manufacturing of the probes.

As an example of a highly specialized probe, the probes for billet testing shall be discussed in this paper. Several identical probes with crystal size 20 by 6 mm are arranged in multi-probe holders. Water jet coupling is used. The spacing between the probes is 15 mm. The task for the billet probes was to cover even those 15 mm without loosing too much sensitivity between the probes. A defocused immersion probe with piezo-composite material was used for this application. The centre frequency of the broadband probe was 4 MHz. The defocusing compensates the narrowing of the sound beam in the near-field range. By this way, a sound beam of almost constant width over a large testing range (depth) was generated.

Such probes based on curved piezo-composites are difficult to manufacture. Since the piezo-composite is mounted under tension, all mechanical production steps have to be carefully controlled. The life-time of an ultrasonic probe is an important criterion of choice. Secondly, the sound beam geometry has to be reproducible for all probes of the same type, so that the change of probes does not affect the overall performance of the testing system.

Several measurements were carried out to verify the probe performance. Artificial defects were introduced into a piece of billet. The test piece was placed into an immersion tank while the probe was moved with respect to the defect. No significant drop of the defect signal could be observed. Obviously, the width of the sound beam perpendicular to the billet axis remained almost constant for the entire billet depth. No narrowing of the sound beam at the typical near-field length was registered. The second measurement was also carried out in immersion technique by moving the probe with respect to a point reflector (steel ball, diameter 3 mm). Two C-scans at two different distances between probe and reflector were recorded. It is very obvious that the lateral width of the beam does not change with depth. Again a beam width of approximately 17 mm is obvious. The spacing of the probes of 15mm in the probe holder therefore ensures proper coverage of the billet.

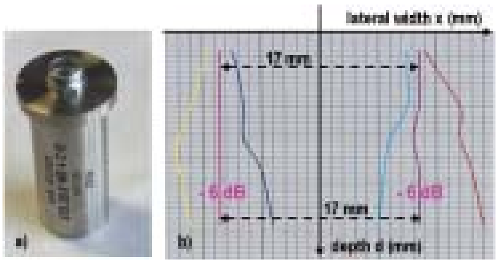


**Figure Probe for Billet Testing**, **a)** defocused piezo-composite probe, 4MHz broadband, **b)** measured sound beam width as a function of distance from the probe (0-200 mm)

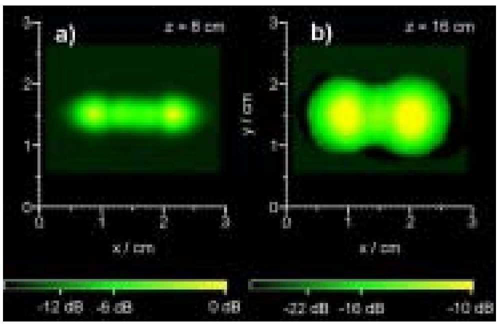


**Figure Lateral sound field pattern** (-3dB) at, **a)** 8 cm and, **b)** 16cm axial distance. Whereas the width remains constant at 17 mm, some broadening occurs in the y-direction which corresponds to the transportation direction of the billets.



KARL DEUTSCH Prüf- und Messgerätebau GmbH+Co KG · Otto-Hausmann-Ring 101 · D-42115 Wuppertal · Tel (+49-202) 71 92 - 0 · Fax (+49-202) 714 932 · info@karldeutsch.de

## Ultrasonic Testing of Black Bars with Stationary Probes

Typical bar diameters for this type of testing system range from 10 to 130 mm. Mostly round profiles are tested, but the system has been adapted also for quadratic, hexagonal or flat profiles. High throughput speeds between 1 and 2 m/sec are standard. For acoustic reasons (to avoid phantom echoes) the pulse repetition rate is often restricted to approximately 1 kHz, which corresponds to a pulse density in the transportation direction of 1 to 2 mm. Since the sound beam diameter of commonly used probes is 7 to 15 mm, full coverage with respect to the transportation direction is achieved. The number of used probes then determines the coverage of the cross section of the profile.

The mechanical frame holds several probe carriers which are distributed around the circumference of the bar. The basic configuration uses three probes which are only used for core defect detection. The standard configuration hold two extra probes per probe carrier which transmits a shear waves under approximately 45 degrees into the material in both circumferential directions. Those angle beams are used to detect near-surface defects. Both circumferential angular directions help to find cracks which are not perpendicular to the bar surface. Higher coverage is achieved by adding extra probes.

Ultrasonic coupling is achieved with guided water jets. The probe carriers rest on the bar surface with hardened skids and are spring loaded to compensate for straightness tolerances. The skids do not have to be changed in accordance with the bar diameter. Since all probe carriers are simultaneously moved, quick changes other dimensions are realised. Although this system is commonly used for black bars, it can of course be used also for bright bars. In that case, plastic skids might be advisable to protect the bar surface.

The bars are fed with a linear conveyor using V-rollers. The bar testing system is surrounded by driver units with pressure rollers for proper guidance of the bars. The testing system is mounted onto a height adjustable test table to compensate for various bar diameters. Often a combination of eddy-current or stray flux testing is carried out to also detect surface defects in the same testing line.

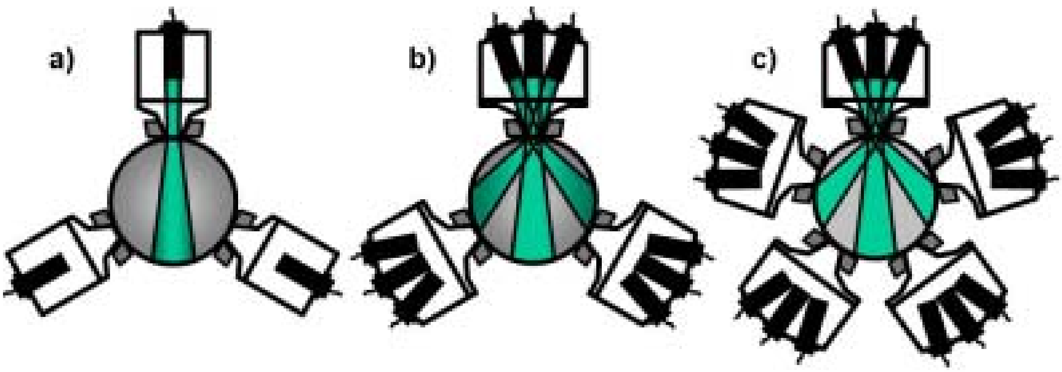


**Figure Principle of Black Bar Testing**, **a)** basic configuration with three straight-beam probes, **b)** standard configuration with nine probes, **c)** high coverage of cross section with 15 probes.

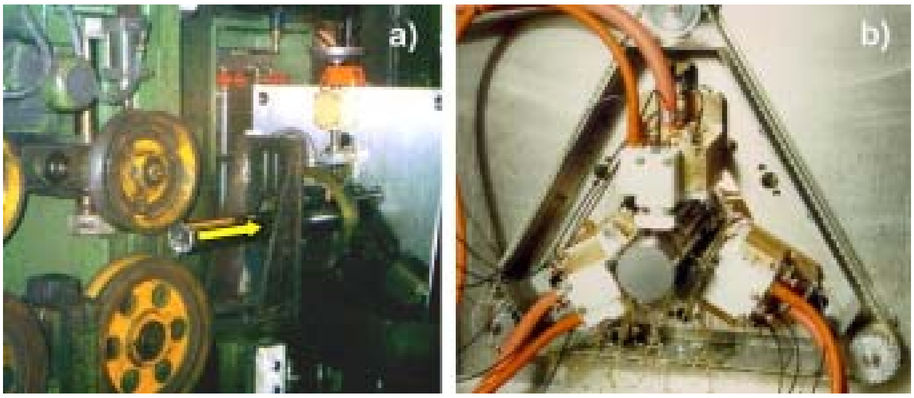


**Figure Testing Mechanics for Black Bar Testing**, **a)** double-V-rollers move the bar into the testing system, **b)** standard configuration with three probe carriers (three probes per carrier) and central diameter adjustment.

## Immersion Testing of Bright Bars with Stationary Probes

Another possibility for bar testing uses an immersion test chamber. This setup is mostly used for bright bars of smaller diameters (15 - 40 mm). The probe holders are ring-shaped cassettes which carry different probes for perpendicular and angular incidence of sound into the bar. Since no mechanical rotation is involved, little maintenance and high signal-to ratio is ensured. Defects in bars are typically oriented in the longitudinal direction and are therefore always detected by the same probe. A precise length determination of such defects is therefore possible. Several cassettes are available for a bar diameter range between 10 and 90 mm. The average water delay between probe and bar surface is 2 cm.

For the angular incidence, special line-focussed probes have been developed and patented. The piezo-electric material is a PVDF-foil which is ideal for the manufacturing of curved probe faces. A low sound impedance offers good acoustic matching with the coupling water. Therefore, such probes produce sound intensities comparable with conventional ceramic-based sensors. In addition the line-focus ensures a highly sensitive inspection.

The water-filled test chamber is mounted onto a height adjustable test table. The chamber can be moved between the test position and the service/calibration position. The test chamber is opened and closed whenever a bar is entering and leaving the unit. This closing mechanics ensures little loss of coupling water, thus providing short untested ends. The number of probes can vary in accordance to the testing task. The higher the number of probes, the more uniform is the coverage of the cross section. For strict testing standards from the automotive sector, up to 23 probes have been used. The testing system includes true-to-position paint marking, good/bad-sorting and in-depth documentation of the test results. A similar set-up with slightly different probe configuration is used for tube testing. In that case the maximum tube diameter is 170 mm.

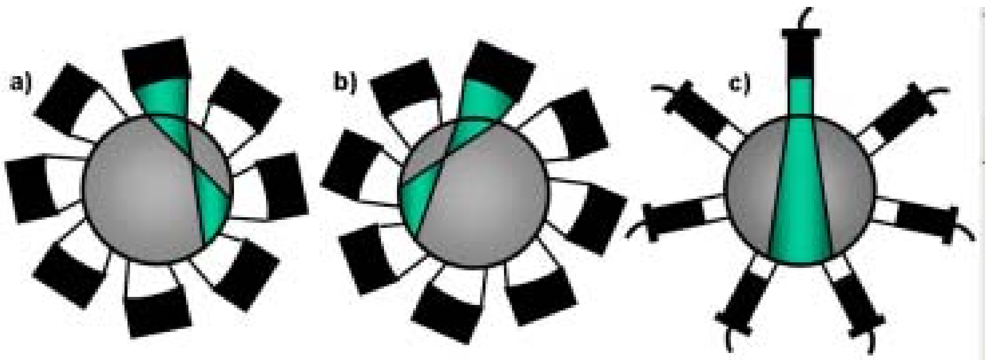


**Figure Principle of Bright Bar Testing**, **a)** angle beam incidence in clockwise direction, **b)** angle beam incidence in counter-clockwise direction, and **c)** straight-beam probes to cover the core region.

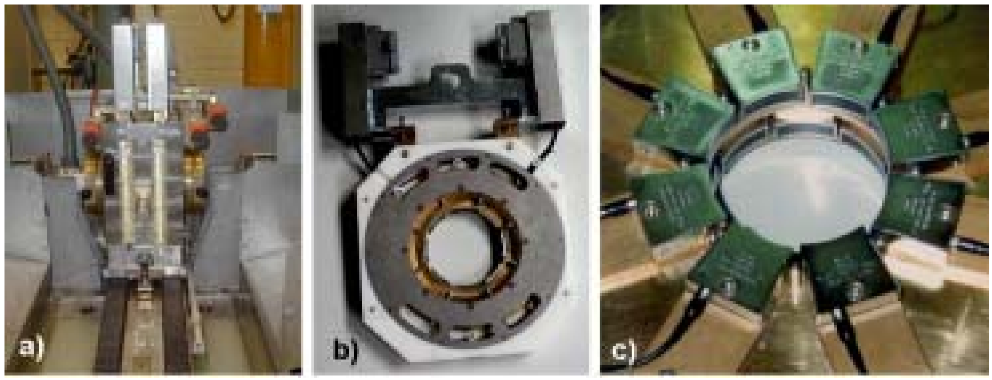


**Figure Mechanics of Bright Bar Testing**, **a)** side view of testing system with water chamber, **b)** probe cassette for large diameters carrying angle-beam and straight-beam probes, c) close-up view of cassette with 16 angle beam probes, the incidence angle is simultaneously adjusted for all probes.

## Component Testing - Applications in the Automotive Industry

The first example shows the inspection of steering racks. The typical dimensions are 700 mm in length and 25 mm diameter. Crucial for the later use of the component is the toothed portion. In addition to the ultrasonic test, a magnetic particle test is applied to check for surface defects. The entire component has an inner hole. A heat treatment during production sometimes causes cracks starting perpendicularly from this inner hole. An automated test was applied to avoid such cracks.

The idea was to scan the toothed portion with a helical test trace. Unfortunately, the complicated geometry did not allow to scan the entire circumference. Echoes from the toothed portion had to be masked out. Therefore, the system contained angle encoders which enable and disable the ultrasonic probes during each rotation. The high through-put rate suggested to use four probes with identical test task. The steering rack is lowered into a small immersion tank and then put into rotation. The probes are linearly moved. An internal longitudinal notch was used for the system calibration. The notch depth corresponds with the critical crack depth which was found empirically. The probe angle was chosen to obtain optimal reflection from the internal notch.

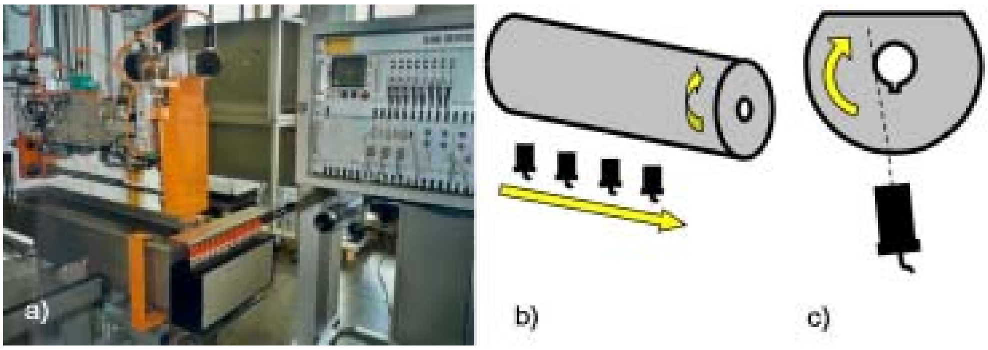


**Figure Testing of Steering Racks**, **a)** testing mechanics with steering rack just before lowering into the immersion tank, **b)** helical test traces with four probes, and **c)** probe incidence angle to detect internal notch.

The second example was realised by ECOMAG in Italy using KARL DEUTSCH electronics and probes. Piston pins are a crucial component connecting the piston rods and the piston. They are produced in very large quantities. Again, a magnetic particle test is carried out in sequence with the ultrasonic test.

The components have diameters between 31 and 62 mm and wall thicknesses between 8.2 and 17.5 mm. The input conveyor uses small V-rollers to transport the pins into the test station. Two rotation rubber wheels produce a spiral forward movement of the pins. Two broadband line focussed probes are mounted above the specimens. Their position shows a lateral offset with respect to the 12 o'clock position of the pins, thus producing angle incidence in both circumferential directions to detect longitudinal defects. Helical test traces are achieved for full coverage of the pins. Coupling is achieved with partially free water jets. Position sensors enable and disable the probes. A sorting mechanics automatically separates faulty specimens into a tray.

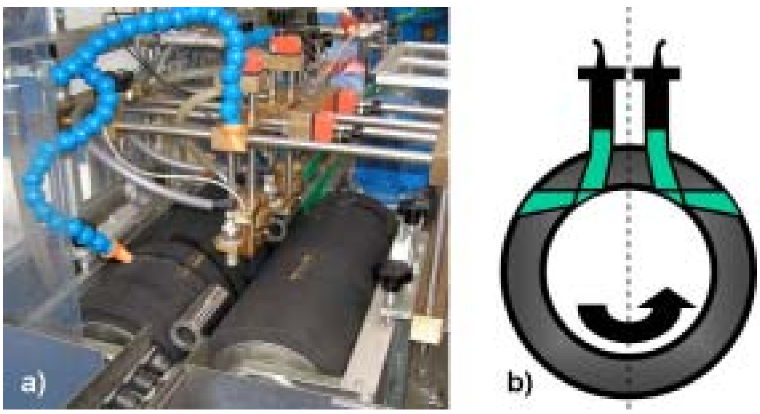


**Figure Testing of Piston Pins**, **a)** testing mechanics with spiral transport of the product, **b)** testing principle with two probes for the detection of longitudinal defects.

## Limitations for Component Testing

The following examples shall demonstrate that certain limitations can make an automated ultrasonic test during production difficult. In many cases, the component geometry is irregular such that the relative movement of the probe with respect to the specimen surface would require complicated motion control. The angles of incidence are sometimes restricted and therefore not all defect orientations might be detectable. If the motion control becomes too complicated, also the investment for a testing system might not be considered worthwhile - sometimes still a questionable approach!

The first example shows manual testing of cams. Internal inclusions are well detected with a delay-line probe. The small size of the component and its irregular shape prevented the installation of an automated testing system. Also, the small dead zones of a delay-line probe in a laboratory setup (contact testing) could not be reproduced in immersion testing.

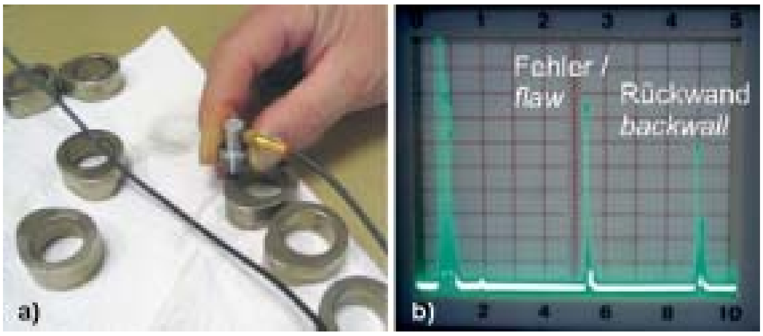


**Figure Cam Testing**, **a)** manual cam testing with delay line probe, **b)** clear defect echo from inclusion.

The second example shows testing of valves. Again, the defects are detected without problems. In this case, immersion testing and angled incidence was used. The complicated geometry of the valves suggested a manual piece-by piece inspection but without automated transportation.


**Figure Valve Testing**, **a)** immersion test setup, **b)** a-scan without defect, **c)** echo from small near-surface defect.

The final example shows a bearing of complicated geometry. Here, the critical areas where defects were located, could not be inspected with ultrasound. The geometrical edges produce echoes which could not be separated from the defect echoes.

**Figure Bearing Testing**, the edges within the bearing surface make an ultrasonic test impossible.

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**Figure NDT Literature**, **a)** the popular „Red Series" on NDT, brief but complete, one NDT method per book (UT, MT, PT, RT etc.), **b)** Ultrasonic Testing – Principles and Industrial Applications (German language), **c)** "Nondestructive Smiling" – stories NOT just about NDT (German language).


KARL DEUTSCH Prüf- und Messgerätebau GmbH+Co KG · Otto-Hausmann-Ring 101 · D-42115 Wuppertal · Tel (+49-202) 71 92 - 0 · Fax (+49-202) 714 932 · info@karldeutsch.de