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Nondestructive Examination of Turbine and Generator Components
Experience with Mechanized Examination Techniques

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1. Introduction

Turbine and generator shafts are highly-stressed components of turbine-generator sets. Examination techniques for rotating turbine-generator set components were the focus of further development efforts following a case of severe damage in the 1980's. Investigation of service lifetimes of turbine components gained considerably in importance. SIEMENS Power Generation Group (KWU) has developed a concept for service life analysis of highly-stressed turbine components which takes into account several factors such as year of manufacture, i.e. the forging process, materials and service conditions to enable power plant operators to initiate timely actions to ensure safe and reliable plant operation.

In addition to material databases which contain not only material criteria but also act as a repository for long-term empirical data, nondestructive examination (using ultrasonic, eddy-current, magnetic-particle and liquid penetrant techniques) has to play an increasingly important role in providing precise descriptions of the condition of examined turbine components. Replica techniques can be used if necessary to conduct examinations to obtain data on material structure and provide information on creep-induced damage.

A fracture-mechanics safety analysis is then carried out on the basis of the obtained test results. This analysis provides information on the safety and reliability of the examined components. The result of the safety analysis, which has a determining influence on continued plant operation, depends on the determined flaw sizes. This explains the considerable importance attached to determination of flaw size.

Over a 25-year period, SIEMENS Power Generation Group has built up extensive experience of ultrasonic examination of turbine/generator shafts and wheel disks subjected to service-induced loads. As part of service life analyses, highly-stressed bolted joints have also been subjected to ultrasonic examination from inside the heat bore for some time now.

Only mechanized examination systems enable reproducible determination and assessment of precise flaw sizes. The above-mentioned experience of determining flaw size using ultrasonic techniques will be explained in this paper.

2. Mechanized UT inspection of turbine components

2.1 Mechanized UT inspection of turbine rotors

Turbine and generator shafts are highly-stressed components of turbine-generator sets [1,2,3]. In spite of overall good experiences, there were a few cases of failure of shafts due to ruptures or bursts , by which basically all manufacturers were affected. The failure mechanisms are all known today, so that such damages can now be prevented with suitable countermeasures.

Brittle failure of a rotor, for example, can occur if internal cracklike material defects reach a certain magnitude, the so-called critical crack size, which depends on stress and fracture toughness. Consequently the main goal of a safety analysis must be to ensure that existing defects are smaller than the calculated critical crack size by a sufficient margin of safety .
At low temperatures, the fracture toughness is lowest. That means that the smallest critical crack size is calculated for cold starts when rotor axis temperature is still low and the total stress (centrifugal, thermal and residual stress) is increasing i.e ratio K_{IC} / σ is lowest.

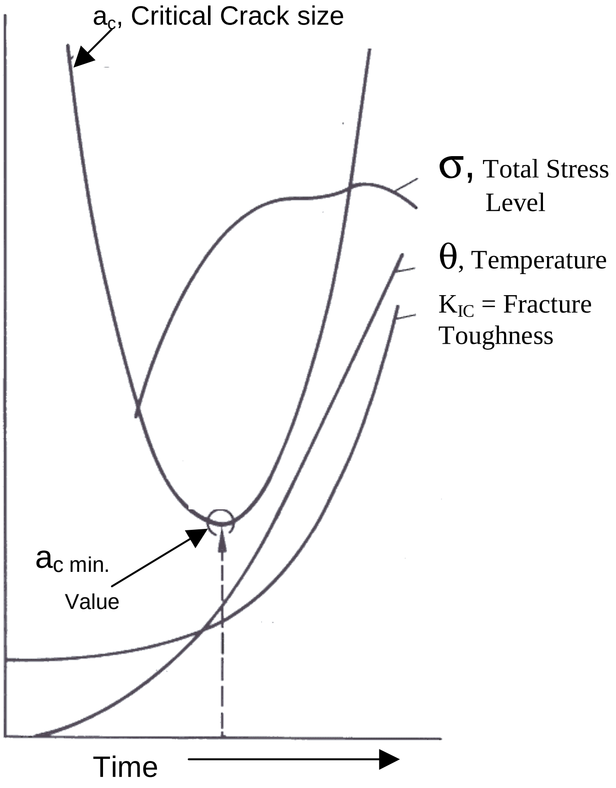

Fig 1 describe schematically the minimum critical crack size during start-up.

In order to demonstrate safety and maintain rotor availability in the future, it is necessary to requalify shafts which have been subject to service-induced loads using the best available ultrasonic testing technique.

Ultrasonic examinations on rotating forged parts are aimed at reliably detecting, sizing and pin-pointing manufacturing-induced flaws which may be relevant to the operational safety and reliability of turbine and generator shafts. Acceptance tests of forged turbine-generator set parts have formed part of the quality management system of turbine and generator manufacturers for many years.
Experience of ultrasonic examination of over 500 shafts was leveraged to enable development of a technology which delivers further improvements in flaw detection, assessment of indications and reproducibility thanks to the use of state-of-the-art computer-aided techniques. The main objective is to detect and size tangentially extended (axially-oriented) flaws in the core area, which measures about 50% of the outer diameter.
The complex surface geometry of rotors subjected to service-induced loading is restrictive in terms of recording all the details of the overall shaft volume, compared to the rough contours of new shafts. This complex geometry is due to the blading, sealing grooves and many other such factors.

The gaps in the volumetric examination which occur as a result have to be covered as far as possible by selecting axial scanning components. Examination of a shaft is performed in a number of stages (paths). Each stage consists of a complete rotation of the shaft and the

associated scanning to record data from 0° through 360°. The scanning density around the circumference of the shaft, i.e. the number of “shots”, is determined on the basis of the search unit sound field (6 dB sensitivity range) and the examination area (core area, boundary area, etc.).
The axial spacing of the scanning paths and the axial scanning component itself are selected so as to ensure overlap of the 6 dB sensitivity range of the sound field in the examination area.

2.1.1 Verification Using the Example of a Feed Pump Shaft

As part of a scheduled major inspection in 1996, the boiler feed pump shaft at a plant operated by a German electric utility was subjected to ultrasonic requalification according to Siemens’ safety concept for forged parts, and in accordance with VGB Guideline R 512 M “Prüfungen betriebsbeanspruchter Läufer und Gehäuse von Dampf- und Gasturbosätzen” (*Examination of in-service-stressed rotors and casings of steam and gas turbine-generator sets*).

The delivery and service data for the machine at the time of the examination were as follows:
- Operating hours: approx. 154,000
- Startups: 1113
- Year of manufacture: 1972
- Material: 34 CrNiMo 6
- Fracture toughness K_{IC}: 1740 N/mm $^{3}/_{2}$
- Finding on receiving inspection, 1971:

The shaft was subjected to ultrasonic examination in the unmachined condition at a frequency of 2 MHz and normal 0° radial scanning. Eccentric indications (eccentricity approx. 55 mm) were found in the shaft body with a reflectivity equivalent to a circular reflector measuring max. 7 mm in diameter and a backwall echo attenuation of approximately 10 dB.

The large number of indications found in requalification of the boiler feed pump shaft necessitated performance of a safety analysis with respect to spontaneous failure. The aim of a safety analysis is to reliably exclude flaws reaching critical size during planned operation under all circumstances. The flaw was conservatively assumed to be cracklike (worst-case assumption), via conversion of the diameter of the reference reflector into a crack length. Flaws which do not initially exhibit cracklike characteristics can spontaneously become cracklike, depending on the sharpness acuity of the flaw after varying numbers of startups, due to low-cycle fatigue, by which point, at the very latest, they become subject to the laws of fracture mechanics.
Adequate safety is provided if the ratio of critical to real reference reflector size is $\geq$ 2.25. The critical flaw size can be determined from the fracture toughness K_{IC} of the component and the service stress.
It was established on the basis of the findings determined in the ultrasonic requalification and the critical flaw size determined in the safety analysis that the safety level was $S < 1$, considerably below the required margin of safety with respect to spontaneous failure. Prewarming of the shaft (leading to higher fracture toughness) also failed to ensure an adequate margin of safety. As a result, it was not possible to return the shaft to service.

Siemens AG Power Generation Group therefore recommended use of a new shaft to enable safe and reliable operation of the plant.

As the feed pump shaft was disassembled, it was possible to perform further nondestructive and destructive examinations to verify the findings made with respect to the feed pump shaft. These examinations were carried out in a joint research and development project by Siemens Power Generation Group and Allianz Zentrum für Technik. The feed pump shaft was examined both manually and using the TUSIS mechanized inspection system (Figure 2).

To determine the influence of turbine shaft profile (geometric restrictions due to forged disks) on the examination result, the turbine shaft was machined to reduce its diameter after the examinations. Mechanized ultrasonic examination was then repeated.

Figure 2

Mechanized ultrasonic examination on the feed pump shaft

In the first mechanized ultrasonic examination, a single indication (in accordance with SEP 1923) with a maximum reflectivity equivalent to a circular reflector approximately 10.5 mm in diameter was detected. Significant backwall echo attenuation (12 dB, search unit EL20) was observed in the area of the indication. It was not possible to determine the length of the reflector due to the shaft profile.

After the first mechanized ultrasonic examination, the turbine shaft was machined and subjected to a repeated ultrasonic examination in the deprofiled condition.

The unrestricted accessibility enabled search units to be used which could not be used in the profiled condition.

The maximum reflectivity of the indication was a little bit lower in both the manual and the mechanized examination. In the manual examination, an axial half-value extension of approximately 30 mm (2 MHz vertical search unit, ∅eff 15 mm) was determined. Assessment of the data recorded in the mechanized ultrasonic examination resulted in a half-value extension of approximately 23 mm (search unit B4S-O, measurement results shown in Figure 4). The backwall echo attenuation was 12 dB, the same value as in the first examination (search unit EL20).

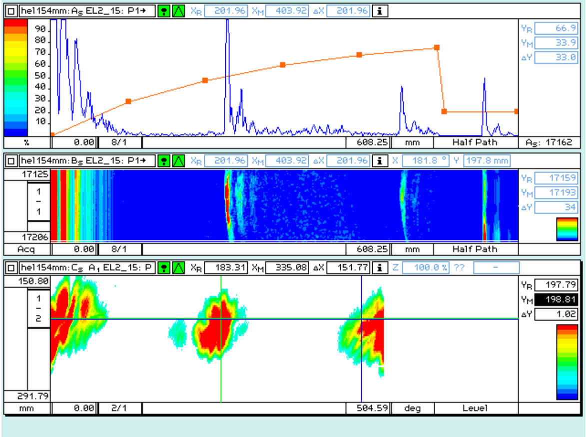

Figure 3
A-, TD- and C-scan of the indication area using search unit EL2-15
(2 MHz)

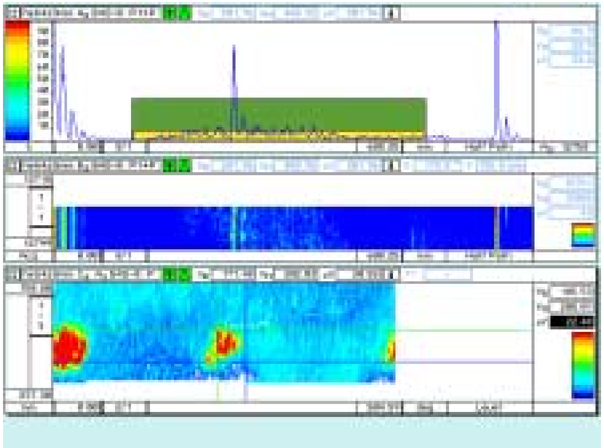

Figure 4
A-, TD- and C-scan of the indication area using search unit B4S
(4 MHz)

Further examinations were carried out with different search units to determine the influence of search unit parameters (frequency, transducer size) on backwall echo attenuation.

Shadow cross-sections of ∅ 9 mm (search unit B4S-O) to ∅ 116 mm (search unit MB2S-O) were calculated from the strongly fluctuating backwall echo attenuations. Calculation of the so-called shadow cross-section is an attempt to calculate an equivalent flaw diameter using the attenuation of the backwall echo given direct scanning of a large-area flaw. Values like path length to flaw, path length to backwall, transducer diameter, frequency and measured backwall echo attenuation (in dB) are incorporated into the calculation.
In addition, the **s**ynthetic **a**perture **f**ocusing **t**echnique (SAFT) was used to determine the position of the indication. This technique enables the position of the ultrasonic indication in the cross-section of the examined turbine shaft to be established on the basis of the determined ultrasonic data (see Figure 5). To verify the examination result, the indication area was removed and subjected to X-ray CT (computerized tomography) examination by the Federal Institute for Materials Testing (BAM) in Berlin. A flaw extension of approximately 17 mm in the axial direction and around 10 mm in the tangential direction was determined using this technique (see Figure 6).

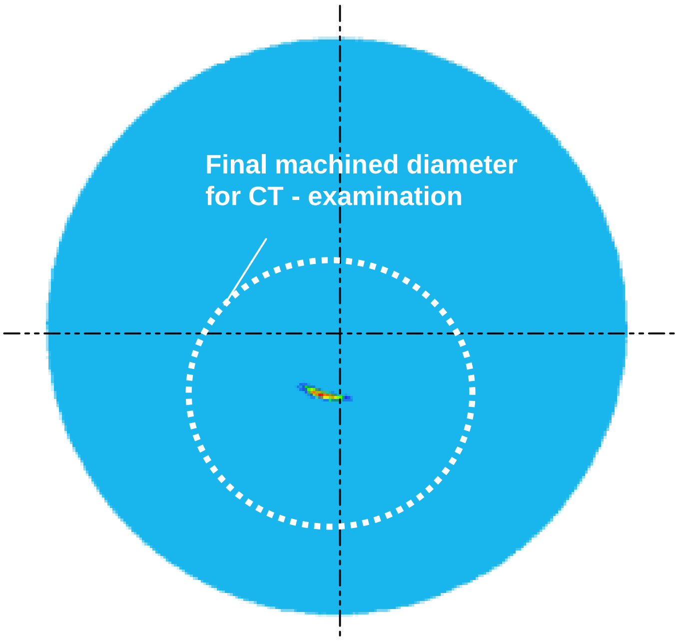

Figure 5
SAFT reconstruction of ultrasonic examination result (2 MHz)

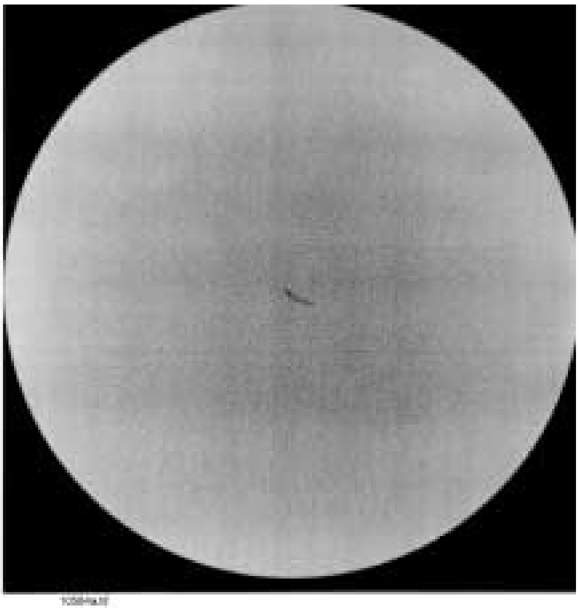

Figure 6
CT examination (by BAM Berlin) of the indication area , Feed pump turbine shaft, detectable flaw width = 10 mm

2.1.2 Metallographic Examination of Indication

The results of fracture-mechanics analysis showed that continued operation of the turbine shaft was not possible due to the indication sizes determined via ultrasonic examination. It was therefore jointly agreed by the plant operator, manufacturer and insurer that further material tests were to be carried out, with the following aims:

- Determination of the cause of the indication, and determination of real flaw size
- Comparison of actual flaw size with the indication size from the ultrasonic examination
- Comparison with the results of the ultrasonic examination carried out at the time of manufacture
- Investigation with respect to service-induced changes.

According to the results of the ultrasonic examination, a manufacturing flaw was present with an axial length of approximately 33 mm and an eccentricity of approximately 51 mm with respect to the shaft center axis. A cylindrical specimen measuring 250 mm in diameter and 90 mm in length was removed from this area by machining to perform the planned further investigations. The position of the specimen was determined such that the ultrasonic indication was located at its center. The results of the CT scan performed on the specimen (Figure 6) show a centrally-located flaw with a tangential extension of approximately 10 mm and an axial extension of approximately 17 mm. The maximum flaw width was estimated at approximately 2.5 mm.

As part of the agreed program, it was necessary to expose the flaw. A compact tensile (CT) specimen was taken from the original cylindrical specimen for this. On the basis of the results of the X-ray tomography scan and further manual ultrasonic examinations after a number of machining steps, it was possible to determine with a high accuracy that the flaw was located at the plane of an erosion-induced groove in the CT specimen. This enabled the fracture of the specimen in a tensile testing machine such that the flaw was located at the fracture surface. The CT specimen was cooled down using liquid nitrogen, and forced to breake open when reaching a temperature of -136°C (measured using a thermocouple).

Figure 7 shows the two halves of the CT specimen after forced fracture. The appearence of the flaw differs clearly from the fracture surface. Dimensions are shown in Figure 8 (extension along long axis: 21.86 mm; extension along short axis: 14.38 mm; area approx. 215 mm²). The surface of the flaw was covered with a crystalline layer. Analysis showed this to be aluminum oxide (Al_2O_3).

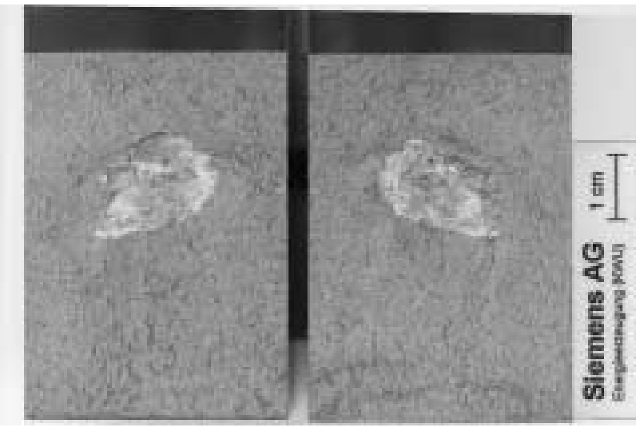

Figure 7
Fracture surface of CT specimen, showing exposed flaw

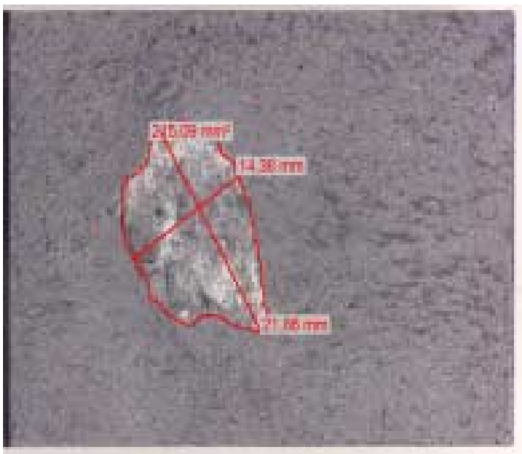

Figure 8
Determination of actual flaw size following forced fracture of the CT specimen

Figure 9
Flaw following forced fracture of the CT specimen

Figure 9 shows the surface of the flaw. It differs clearly from the surrounding fracture surface of the CT specimen, and appears macroscopically to be smoother, viewed. Fractographic examination using a scanning electron microscope, in addition to provide information on the type of flaw, was aimed in particular at clarifying whether a service-induced change has occurred. A statement for this is from the following reason unambiguously possible.

Deliberate tearing of the specimen following cooling to -136°C results in predominantly brittle forced rupture, characterized in micro-fractographic terms by cleavage faces. The flaw results from manufacture of the forging. Such structures also exhibit a characteristic morphology in the form of smooth surfaces. Service-induced changes also feature characteristic structures, as is known from the results of damage investigations and examination programs [12]. These structures are clearly distinguishable from faces planes, dimples and manufacturing flaws.

The flaw surface and the flaw/fracture surface transition were systematically examined using the scanning electron microscope. The flaw surface (Figure 10) exhibits the typical structure, with inclusions characteristic of manufacturing flaws. These are internal voids with exposed surfaces, which were not adequately compressed/closed by the forging process. The aluminum oxide inclusions are distributed across the whole flaw. The flaw boundary (designated F) and the adjacent fracture surface (designated S) are shown in Figure 11. Cleavage faces are characteristic of the fracture structure arising on forced rupture of the specimen.

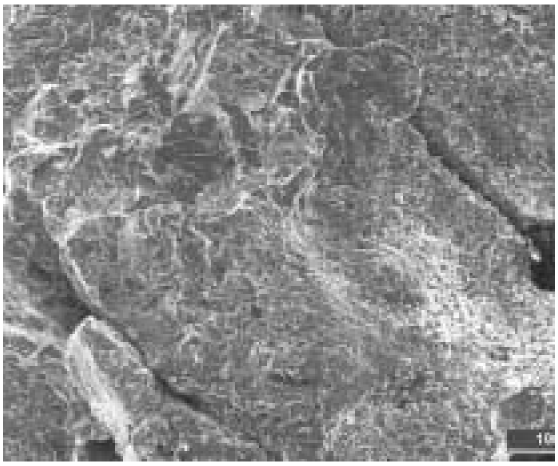

Figure 10 Flaw surface

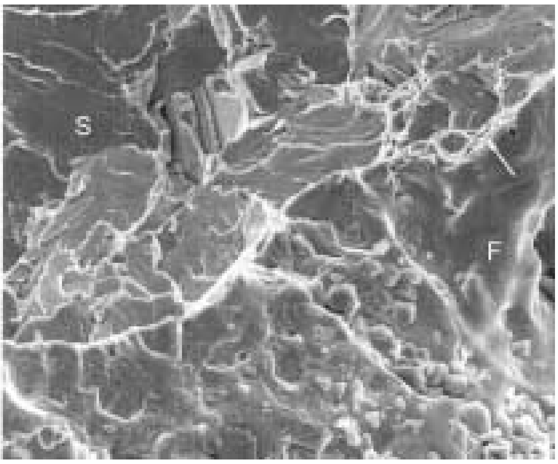

Figure 11
Flaw boundary (F) with transition (marked with arrow) to fracture surface of CT specimen (S). Aluminum oxide inclusions are distributed across the whole flaw.

The results of the fractographic analysis show that the indications arising from the ultrasonic examination were caused by a manufacturing flaw in the form of a void (shrinkage cavity) inadequately closed by forging, in conjunction with an accumulation of aluminum oxide. There were no indications of service-induced changes.

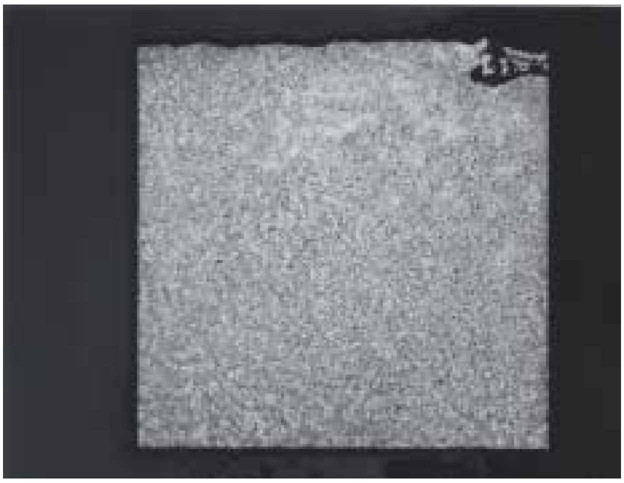

Figure 12 Section through the flaw; the top edge of the section corresponds to the surface of the flaw.

Sections through the flaw were made using the other half of the CT specimen (the part of the specimen not examined using the scanning electron microscope). The section was made through the center of the flaw (Figure 12). Analysis using polarized light shows that the voids are filled with aluminum oxide (Figure 13).

Figure 13
Flaw center; the aluminum oxide inclusions become optically active when polarized light is used.

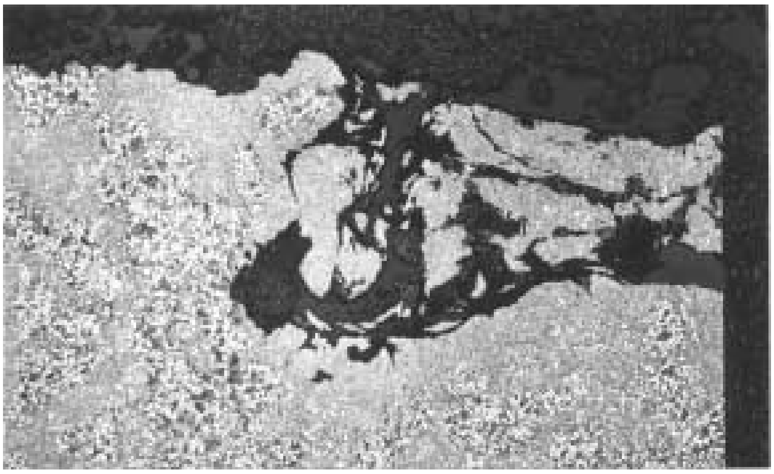

Figure 13 a
Flaw center; inhomogeneous structure consisting bainite and ferrite/perlite.

The structure exhibits extensive inhomogeneities in the form of bainite structure and ferrite/perlite components (Figure 13). Micro-hardness measurements highlighted significant differences in hardness between the ferritic/perlitic structure and the bainite (approximately 200 HV and 320 HV respectively).

In summary, it can be stated that the cause of the ultrasonic indications is a manufacturing flaw in the form of a void inadequately closed by forging and non-metallic inclusions (aluminum oxide). This flaw was detected already at the ultrasonic examination performed on the shaft during manufacture in 1971. This test result is quite comparable with the result of the requalification test. According to the examination report, the eccentricity was given as 55 mm, reflectivity as equivalent to a circular reflector 7 mm in diameter, and the backwall echo attenuation as 10 dB. Comparison with the currently determined values (eccentricity 51 mm, max. reflectivity equivalent to a circular reflector 11 mm in diameter, and backwall echo attenuation max. 12 dB) shows that comparable indications were present at the time of the initial receiving inspection.

The flaw was exposed using a fracture-mechanics specimen, and examined under a scanning electron microscope. Service-induced changes - such as sharpening of edges or flaw growth - were not observed.

2.1.3 Conclusions with Respect to the Use of Mechanized Ultrasonic Volumetric Examination for Inspection of Turbine Shafts

The use of images in ultrasonic examination of axisymmetric components brings a significant improvement in the description and assessment of examination results. The use of TD images, 2-D SAFT tomograms and three-dimensional representation of the test object enable clear description of the position and distribution of reflectors in the components.

Combined use of

- DGS evaluation
- Evaluation of echo dynamics
- 2-D SAFT reconstruction
- Assessment of backwall echo

enables complex assessment of ultrasonic results and estimation of flaw size in forged parts.

Consideration of backwall echo attenuations improves flaw size determination, particularly with respect to large flaws, whose ultrasonic response (reflectivity) exhibits only limited correlation with flaw size.

The DGS method, with application of a correction factor, has proven suitable for determining flaw size. The initial flaw size to be used for further calculation is obtained from the US-measured size, taking into consideration a correction factor, which compensates for the ratio between the true flaw size and the US reference reflector size.

Calculation of a shadow cross-section using the measured backwall echo attenuations showed that the values measured using the <u>4 MHz search units B4S and EL4(20)</u> led to <u>flaw sizes</u>, <u>which were very close to the actual flaw size.</u> 2 MHz search units proved unsuitable for this method, as the calculated shadow cross-sections were disproportionately large.

The examined reflector was originally positioned approximately 51 mm from the shaft center, with an axial-tangential orientation. This was practically the optimum orientation for the ultrasound beam, which also explains the maximum measured reflectivity (equivalent to a circular reflector 10.5 mm/8.5 mm in diameter respectively) at 0° incidence.

It is not possible to assess the effects of flaw orientation, flaw type and flaw surface quality on the measured reflectivities and backwall echo attenuations.

Analysis of actual flaw size, given a flaw area of 215 mm², converted on the basis of a circular reflector 16.5 mm in diameter, and the reflectivities equivalent to a circular reflector approx. 11 mm in diameter measured in the ultrasonic examinations, confirms that the application of a correction factor to the calculation of true reference reflector size from the ultrasonic indication is necessary and correct.

The final examinations confirmed that the indications determined using ultrasonic examination were unacceptable, and that the withdrawal from service of the feed pump shaft agreed with the customer was justified.

Safe and reliable operation of the turbine shaft could no longer be guaranteed.

SIEMENS Power Generation Group has carried out ultrasonic examinations on turbine shafts (OEM and non-OEM) subjected to service-induced stress since 1983. The extensive experience built up as a result confirms the effectiveness of the ultrasonic requalification process. Analysis of 500 examinations performed on turbine shafts clearly shows that indications were frequently detected, particularly in older turbine shafts. For example, of 178 turbine shafts manufactured before 1960, indications equivalent to a circular reflector size > 5 mm in diameter were found in 48 turbine shafts (27% of the examined shafts), with 3% even exhibiting flaws equivalent to a circular reflector size up to approximately 18 mm in diameter. A further 48 turbine shafts showed indications equivalent to a circular reflector size > 2.5 mm in diameter.

This experience provides the reason for the recommendation to perform ultrasonic examination on turbine shafts subjected to service-induced stress contained in VGB Guideline R 512 M.

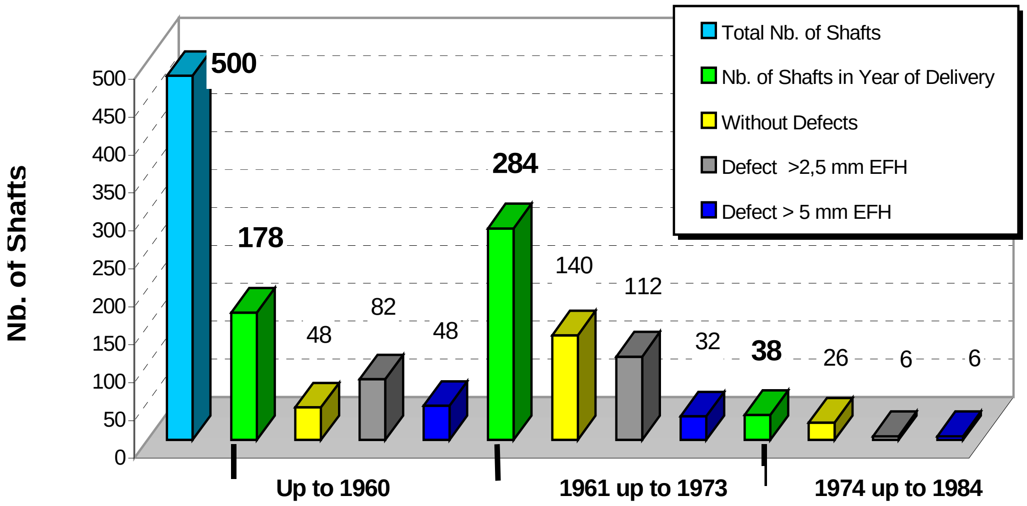

Figure 14
Analysis of examination results as a function of year of delivery of turbine shafts

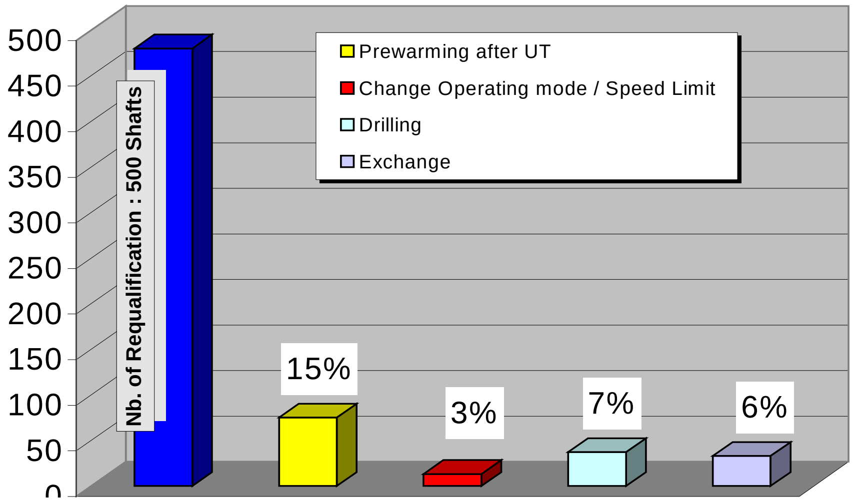

Figure 15
Analysis of actions taken after performance of ultrasonic examinations

Based on the above-mentioned UT findings, different measures have to be taken to ensure safety and availability for future operation.
After UT-requalification, 15% of shafts had to be prewarmed to allow further operation. In the case of 3% of shafts, instructions were given with regard to operational measures. In 7% of shafts, the findings were eliminated by drilling or enlarging the existing bore. Finally, for 6%, i.e. 30 shafts, replacement was recommended.

2.2 Mechanized Ultrasonic and Eddy-Current Examination of Bores in Turbine Shafts.

A large number of turbine-generator-set rotors contain a central bore. In the past, in order to obtain reliable data on the material properties of the forged part, axial or radial bores were made during manufacture of the forging to enable material specimens to be taken, in certain cases with a view to remove indications.
It is known that stresses are increased in the vicinity of the bores, and therefore the critical flaw size is much smaller than in the remaining volume of the rotor.
It is therefore very important to inspect the zones adjacent to the bore surface using suitable testing techniques. The mechanized test techniques available today permit rational and reliable compilation of information and assessment of findings.
SIEMENS Power Generation Group examines bores in turbine and generator shafts using the BORIS portable bore inspection system. This system consists of a manipulator with drive unit, a digital ultrasonic device and an eddy-current unit. It ensures high-sensitivity eddy-current examination of the cylindrical bore surface as well as ultrasonic examination of the zone around the bore surface. The combination of mechanized eddy-current examination (as a surface crack detection technique) and ultrasonic inspection of the zone adjacent to the bore enables high-sensitiv examination for forging flaws in bore areas, thus allowing reliable data to be provided on the operational safety and reliability of turbine shafts.

Figure 16
BORIS bore inspection system during examination of an axial bore

Eddy-current examination is carried out using high-sensitivity rotary probes equipped with both absolute and differential probes. Examination is carried out using the absolute probe, with verification using the differential probe in the event of an indication.

Ultrasonic examination is carried out using the TOMOSCAN multi-channel digital ultrasonic device. Four focused two-crystal probes enable scanning in four different directions. This ensures reliable detection of flaws in an area up to 30 mm from the bore surface.

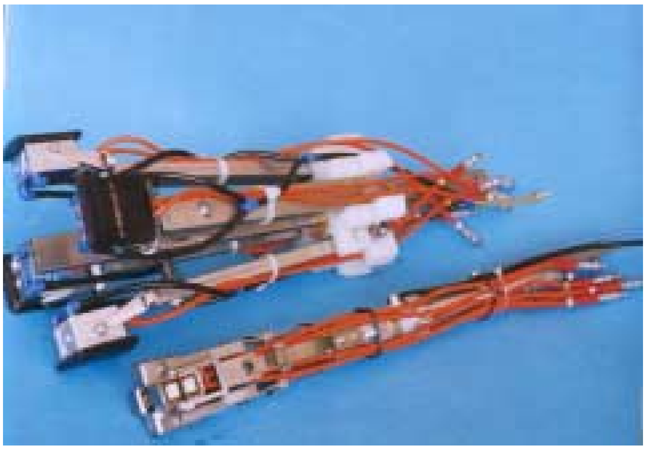

Figure 17
UT probes for ultrasonic bore examination

Figure 18
Rotary probes for eddy-current bore examination

2.2.1 Example of a Bore Inspection on a High-Pressure Turbine Shaft

An examination carried out on a high-pressure (HP) turbine shaft will be used to demonstrate the capabilities of the BORIS bore inspection system.

A single indication (equivalent to a circular reflector size 5.5 mm in diameter) was identified in the gland area during ultrasonic volumetric examination from the outside surface of an HP turbine shaft of Russian design (LMZ). This indication was located approximately 26 mm from the surface of the through axial bore. No indications were identified during surface crack testing of the axial bore. Ultrasonic examination from the axial bore confirmed the indication detected from the outside. An angular oriented indication (26-31 mm from the bore surface) approximately 62 mm long was identified. Analysis of the recorded echo dynamics enabled a radial extension of 7 mm to be determined. Figure 19 shows the results of the ultrasonic volumetric examination (from the outside surface) and the ultrasonic examination from the bore.

Fracture-mechanics analysis of this flaw led to the assessment that the flaw was unallowable in terms of safe and reliable continued operation of the turbine shaft.

It was decided to machine away the flaw area in stages while carrying out a surface crack examination (MP examination) to determine the actual flaw size.

The indication was exposed at a depth of 31 mm from the original bore diameter. Figure 21 shows that the indication exhibited an axial extension of approximately 38 mm at this depth.

However, this does not represent the complete axial extension of the flaw, as the tube-type forging flaw exhibited an oblique orientation in the axial direction, and this meant that the full extension could not be exposed.
Assessment of all examinations carried out (step-by-step machining-away of the indication area was carried out in 2.5 mm stages, with an MP examination carried out after each stage) showed that the total axial extension of the tube-type forging flaw was 58 mm, and the distance from the original bore diameter was 26 - 36 mm.

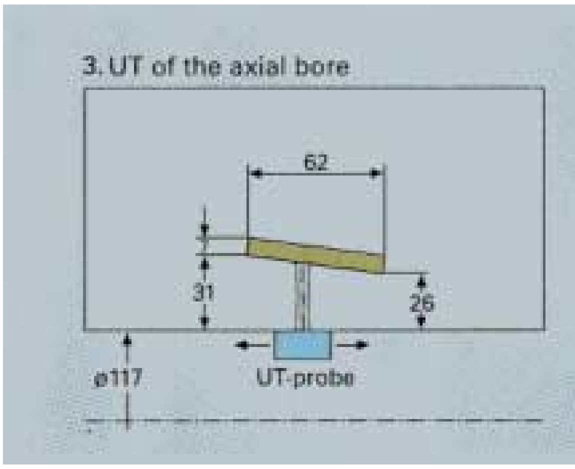

Figure 19
Results of ultrasonic volumetric examination
and ultrasonic bore inspection on HP turbine shaft

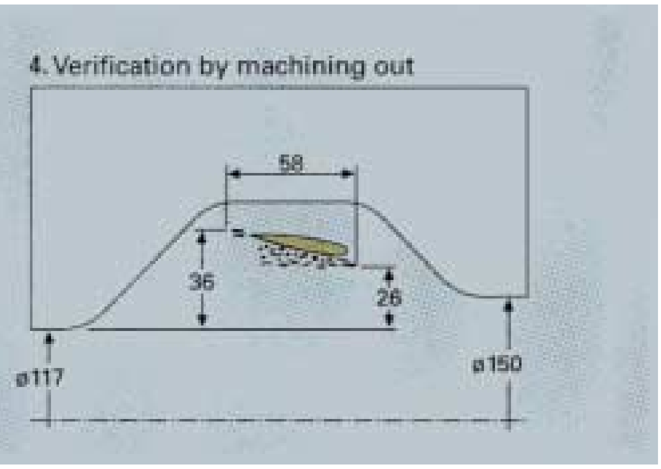

Figure 20
Profile of axial bore after machining away of flaw area
Determined actual flaw size: 58 mm

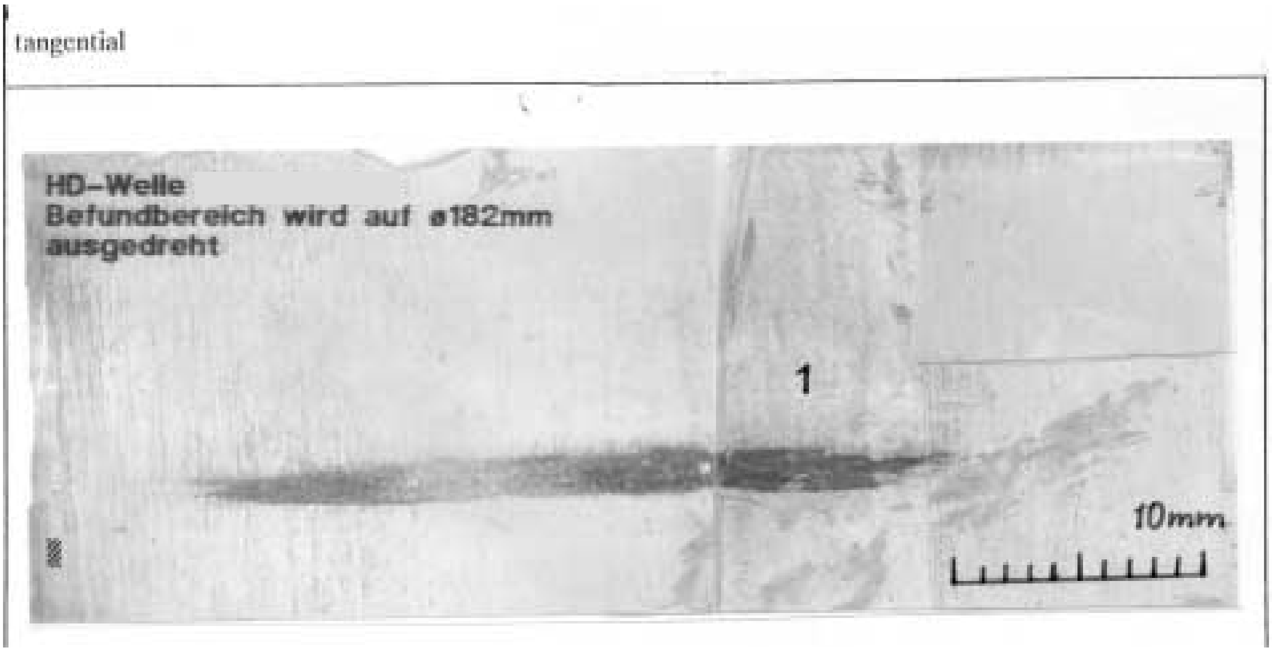

Figure 21
Results of MP examination of axial bore
during machining away of indication area
Depth from original bore surface: 31 mm

Thanks to the measuring accuracy, relatively good agreement was obtained between the flaw size determined using ultrasonic bore inspection and the actual flaw size.

The described example of ultrasonic examination of an HP turbine shaft shows that the combination of ultrasonic volumetric examination (from the outside surface) and inspection of bores from the bore surface using the BORIS inspection system provides satisfactory data on the condition of turbine and generator shafts. The above-mentioned techniques enable detection, sizing and orientation description of all stress-relevant flaws.

Out of a total of approximately 500 examined turbine shafts, indications were removed by machining away or increasing the bore diameter in 35 cases, enabling the turbine shafts concerned to be returned to service after the corrective actions.

2.3 Mechanized Ultrasonic Examination of shrunked on Disks on Turbine Shafts

2.3.1 Disk Inspection Robot for Examination of Turbine Rotors in the Assembled Condition

Disks of low-pressure turbine rotors are highly-stressed components which are subject to aging as a result of operational influences. Increased mechanical stresses arise, in particular, in area of the shrink fit. Stress corrosion cracking may occur as a result of these stresses and the temperatures during turbine operation. The branching intercrystalline stress corrosion cracks occur preferentially on hub inside surfaces and on the axial antirotation devices of the wheel disks, and exhibit axial-radial orientation, due to the tangential direction of the main stress.

As a result, unallowable crack growth, or, in extreme cases, disk rupture, may occur after long periods in service. In Germany and other countries, therefore, inservice inspections are required to be performed on disks. Recommendations with respect to this can be found in VGB-R 512 M. Inspections are carried out every 50,000 hours service for older turbine designs. Ultrasonic examination of disks was previously carried out on a partially-mechanized basis using an inspection manipulator. This inspection necessitated placing the turbine shaft on a turning gear, and turning it at a constant speed of 2-3 revolutions per minute.

Fifteen years of experience of mechanized ultrasonic examination of turbine disks was put to use in the development of a new seven-axis inspection robot. This new system is capable of performing ultrasonic inspection of disks with the turbine rotor in the assembled condition. In addition, the robot uses a laser-beam measurement system to record geometric data on disk profile, which are essential for such inspections. The seven-axis inspection robot thus also enables inspection of disk-type rotors for which no drawings are available (i.e. disk-type rotors manufactured by other suppliers). The selection of the UT-probes and the probe positions are calculated. Once the settings for the area to be inspected have been calculated, and the required UT probes have been fixed, the operator clicks on the appropriate option using a mouse to command the inspection robot to move to the calculated position and couple the UT-probes.

Once the 0 – 360° scan has been completed, the operator returns the robot arm to the starting position to enable fitting of the UT-probes for the next inspection stage.

The use of this inspection robot enables test times for disk inspections to be significantly reduced, particularly in terms of the analysis effort necessitated in the event of findings. The inspection system has already been used in examination of five LP disk-type rotors in nuclear power plants in the USA and Germany. Complete inspection of a SIEMENS disk-type rotor can be performed in five shifts.

Figure 22
Seven-axis robot during disk examination of an LP turbine shaft in the assembled condition

To inspect the whole hub inside surface of a disk and its anti-rotation device holes, each disk hub is divided into a number of axial inspection zones. The edge zones of the disk are inspected using the single-probe technique. The central zones are inspected using the tandem technique, whereby a search unit must be positioned on each face of the disk. One search unit acts as a transmitter, and the other as a receiver.
Four inspection techniques can be deployed in examination of disks:

- <u>Tangential scan:</u>
- <u>Corner trap technique:</u>
- <u>Radial scan:</u>
- <u>Time-of-flight diffraction (TOFD) technique:</u>

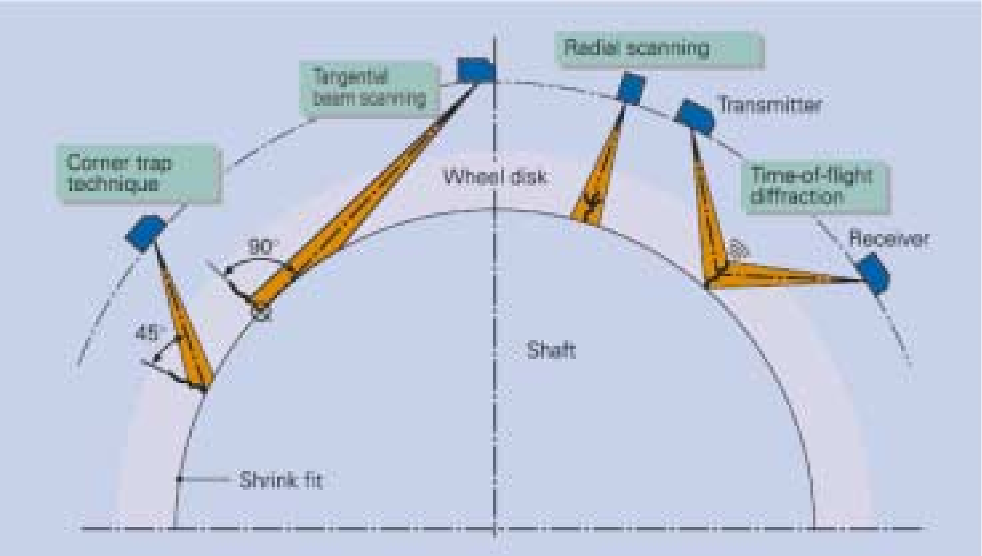

Figure 23
Inspection techniques for ultrasonic wheel disk examination

To determine flaw depth in the radial direction with respect to the wheel disks, the reflectors found are examined by means of vee scans. Two shear-wave search units are positioned in relation to each other such that the ultrasound impinges, and is reflected, at an angle of 45° to the hub inside surface.

With branching stress corrosion cracks, an indication from the crack tip area is obtained in advance of the echo from the hub inside surface.

The TOFD technique has proven an effective analysis method, as it enables high-precision determination of crack depth. Tangential scanning (90°) or the corner trap technique (45°) can be used as the search technique.

The disk inspection system which was introduced in 1987 is a most reliable and effective inservice inspection tool to verify LP turbine disk-type rotor integrity. About 650 disks with between 24,000 and 130,000 hours service have so far been successfully inspected. In addition, 15 wheel disks on LP rotors in fossil-fired power plants have also been inspected.

Fewer than 1% show cracking in the hub bore which was verified by metallographic investigation after disassembly of the disks. Experience shows that the inspection system is sensitive to detect and size even small cracks. Destructive testing of the disks concerned by the findings confirmed the position and extent of the indications detected by ultrasonic examination (result of TOFD measurement: 24 mm/actual crack depth: 26.7 mm).

SIEMENS' vast experience of ultrasonic examination of disks on turbine shafts provides the basis for high inspection reliability, where the ability to distinguish between cracks and score marks is required. Qualification of the inspection system using a test disk, with artificial flaws in all inspection zones, was a requirement for using the inspection system in nuclear power plants.

Further development of the inspection system ensures optimized inspection times with the turbine shaft in both the assembled and disassembled condition. This enables solutions to be tailored to specific outage-related requirements and resultant customer wishes. The advantages of the seven-axis robot described here are very useful in particular when performing inspections with the turbine shaft in the assembled condition, and in analysis of disks with UT- findings.

Currently ongoing further development of inspection techniques, and deployment of phased-array technology in disk inspection, are expected to drive continuing optimization of the inspection process, thereby cutting inspection times still further. The phased-array technique entails setting the different angles of incidence for ultrasonic examination electronically so that it is no longer necessary to replace UT-probes to ensure calculated angles of incidence for scanning.

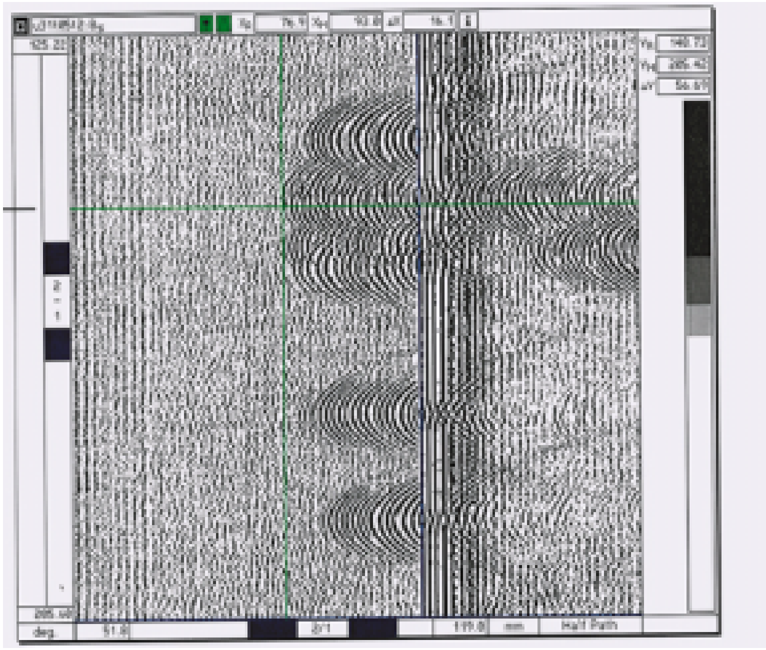

Figure 24
Indication from a wheel disk inspection (analytical measurement using TOFD technique).

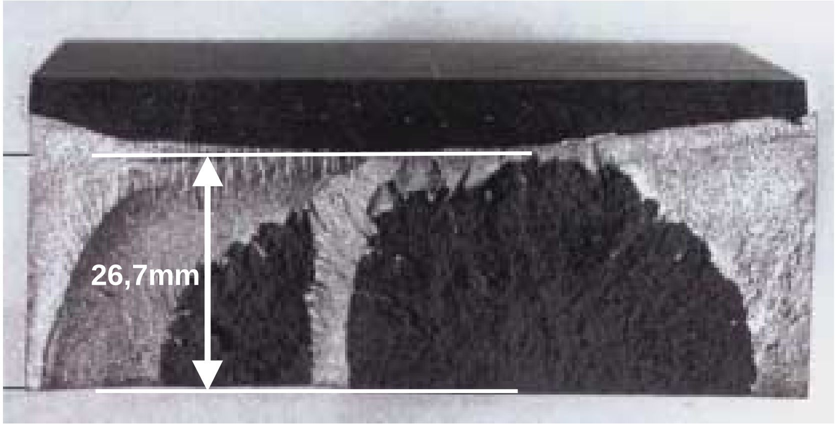

Figure 25
Crack detected during wheel disk inspection, investigated using destructive methods

2.4 Mechanized Ultrasonic Examination of Casing Joint Bolts

2.4.1 Manipulator for Inspection of Bolt Holes

Casing joint bolts were previously subjected to MP examination in the disassembled condition during outages, with borescopic examination of the heat bore if necessary. Ultrasonic examination from the end face of the bolt proved unsuitable for detecting small incipient cracks in the thread root. Due to sonic beam divergence and the geometric reflections from the thread starts, ultrasonic examination from the end face of the bolt only enabled detection of larger incipient cracks.

For this reason, recent years have seen an increasing tendency to complete disassembly of casing joint bolts and performance of MP examination.

To examine casing joint bolts for small incipient cracks on a nondestructive basis, without disassembling the bolts, an inspection system was developed which examines highly-stressed areas of the bolts using ultrasound. A bolt hole manipulator moves a focused two-crystal probe along a helical path through the hole. The focused UT- probes scans obliquely forward at an angle of approximately 70° so that stress-relevant areas are examined. This enables reliable detection of incipient cracks upward of a depth of approximately 1 mm in the thread root of the bolt.

The new inspection system enables:

- Inspection of bolts for incipient cracks in the assembled condition
- Performance of inspections during short outages
- Comparative measurements (inservice inspections) thanks to digital data recording/archiving
- Problem-free inspection of bores in shafts of other highly-stressed machine components in the diameter range 20 - 30 mm
- Rapid inspection thanks to optimized manipulation and ultrasonic examination technology.

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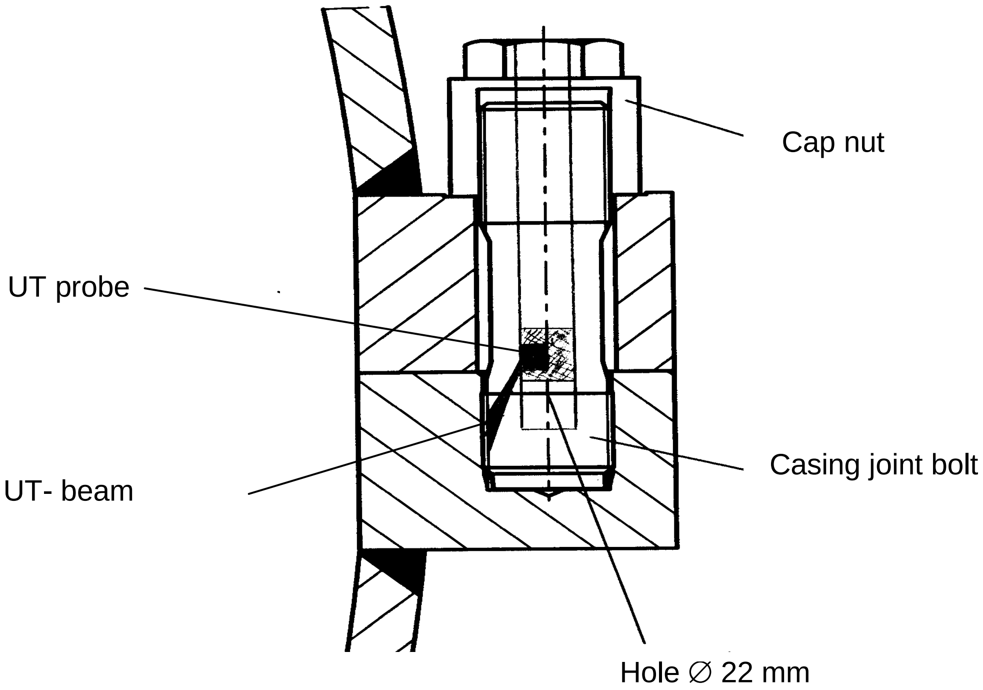

Figure 26
Schematic of examination of casing joint bolts in the assembled condition

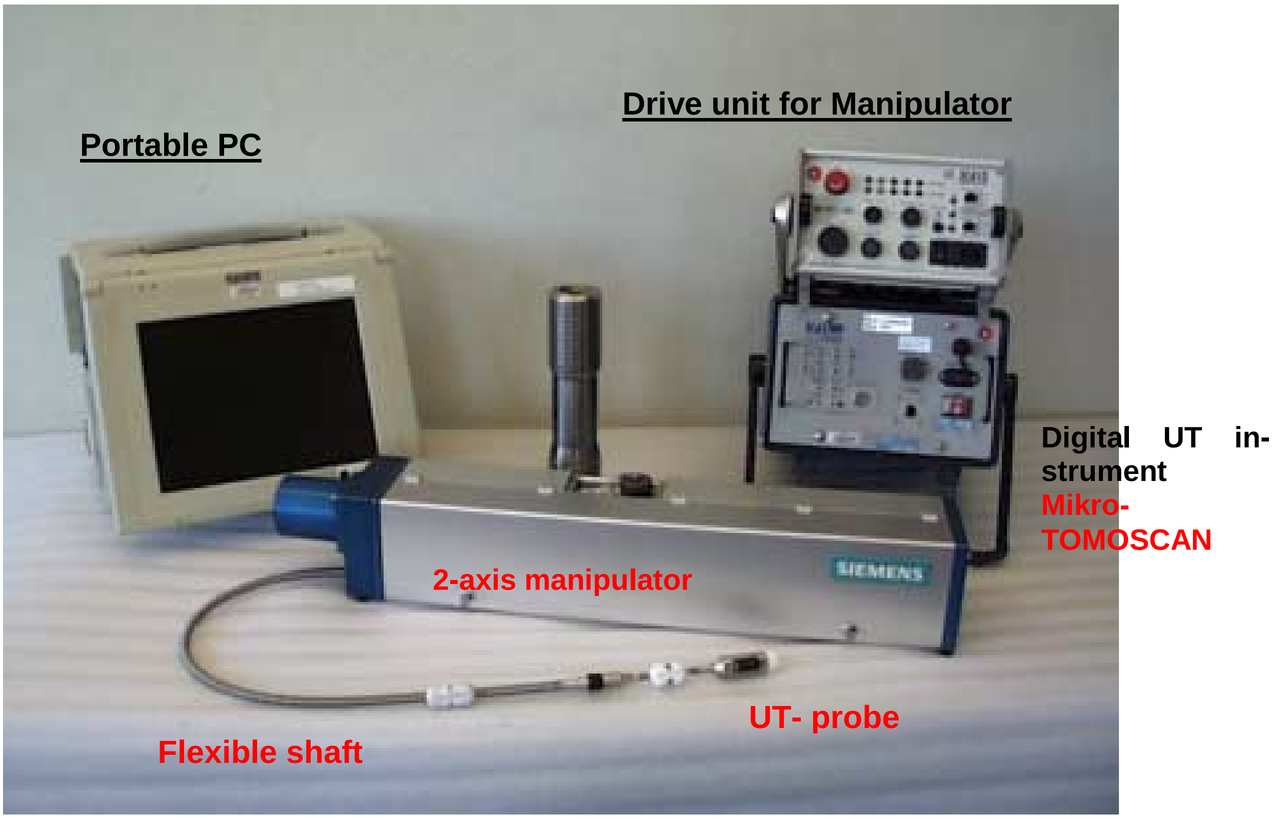

Figure 27
System for mechanized inspection of holes in bolts

Figure 28
System for inspection of casing joint bolts

Figure 29
Incipient crack in the thread root of a bolt

Conclusions

The use of nondestructive examination techniques for performing inspections on power plant equipment is starting to play an increasingly significant role. Nondestructive examinations have to be performed on a wide range of turbine and generator components during power plant outages, which generally have to be completed within a very short timeframe. For this reason, mechanized inspection systems are increasingly being used, enabling high-sensitivity examination with absolute reproducibility. This is particularly important with respect to examination of components subjected to periodic inservice inspections (e.g. wheel disks, generator rotor retaining rings). The inspection techniques and assessment methods used must guarantee direct intercomparison of measurements.

In addition, inspection systems which enable nondestructive examination of components in the assembled condition are also gaining in importance. Such systems allow minor disassembly effort and expense to be avoided.

The advantages of this new approach were examined using the example of a new type of inspection robot for ultrasonic examination of wheel disks. Wheel disk examination was performed on an LP turbine shaft in the assembled condition in a nuclear power plant in the USA. A range of aspects (limited space on the turbine deck, crane capacity, short outage length) played a role, leading the power plant operator to have the examination carried out in the assembled condition. Parallel examination of an LP turbine rotor in the assembled condition and an LP turbine rotor in the disassembled condition during an outage in a German nuclear power plant is planned for 2001.

A cost-benefit analysis shows that mechanized nondestructive examination techniques not only deliver optimum flaw detection capability and the required reproducibility, but also ensure a measurable reduction in outage time, leading to direct cost reductions for power plant operators.

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