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Use of Non-Destructive Testing (NDT)
in Engineering Insurance

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SUMMARY

Today society uses sophisticated civil structures and complicated machinery the safety of which is related to the integrity of the components the units are composed of. Typical examples would be bridges, cars, aeroplanes, pressure vessels, and nuclear power plants. It is imperative for the safe usage of these complicated technical units that monitoring of the integrity of the most critical components is done properly as a loss prevention routine. At the same time this in-service testing ensures a minimising of operational outings of the units, and thus also pay back from the industrial investments in question.

Non-destructive testing (NDT) is widely used in manufacturing to ensure the integrity of the components produced. Machine diagnostics is used for preventive maintenance, failure analysis and for the post-care of damages. In all these areas NDT-methods are utilised. It is obvious that to ensure the safe use of more and more complicated and sophisticated machinery and structures where the strength of materials is utilised to its ultimate rendering ever decreasing safety margins, the use of testing the materials non-destructively usually in situ operational modes is imperative. Thus the field of non-destructive testing plays a significant role in producing quality products and thus ensuring a reliable and efficient performance of components, mechanical units and industrial plants.

The paper reviews the basic idea of using non-destructive testing, explains the role of how non-destructive testing is an important part of loss prevention connected to the insurance world. Hereby, the importance of risk based inspection, inspection qualification, and the certification of the NDT-operators themselves is discussed. A short history of the main six so called classical NDT-methods is given. Also their physical principles and typical applications of loss prevention utilising these methods are presented. Finally, some recommendations are laid out on how NDT-inspections adds value and reliability to plant operation.

KEY WORDS: Loss Prevention; Non-destructive Testing; Risk Based Inspection and NDT.

DESCRIPTION: The paper discusses the role of Non-destructive Testing (NDT) in engineering insurance and provides examples of where industrial losses have been prevented using NDT.

Use of Non-Destructive Testing (NDT) in Engineering Insurance

THE IDEA OF NDT

A human being has an incredible skill to perform diagnostics of machines including the human body by using the four senses we have - i.e. seeing, hearing, smelling and mechanical feeling - when the information is processed and combined with experience, that is historical facts. The processing is extremely fast and complex and brings out better results than e.g. any modern computer, be it a neuro-based system, can produce.

When our senses do not give enough information in order to make an objective diagnosis, we can "prolong our senses" by taking into use more physical phenomena. We then make the "invisible become visible " by being able to look around corners with endoscopes, see the inside of a material with x-rays or ultrasonic waves, or view the heat of a component as different colours as we do in thermography, or finally measure the vibration of a part objectively and not only realising that the part is shaking.

In short, one could claim that primarily the idea of using NDT-methods is to find discontinuities in the material, mostly cracks or thinning caused either by erosion or corrosion. In other words, the first objective of NDT is to locate the discontinuities. Thereafter the second objective in to measure the dimensions and directions of the discontinuities. When this is done, the following step is to evaluate if a flaw conforms to the stipulated acceptance criteria or not. For stipulating the criteria one would have to know the critical flaw size and the speed of extension of the flaw. To calculate these two factors one has to utilise fracture mechanics. As base facts fracture mechanics utilises the dimensions of the flaws found out via the use of NDT-methods, the applied stress, and the fracture toughness of the material in question, thus producing acceptance criteria for different components and geometries.

Preset criteria are followed for manufacturing industrial products and NDT-findings accordingly compared with these for acceptance. On the other hand, when NDT is used in in-service inspections, somewhat less stringent acceptance criteria are often used for normal inspection purposes. If the components are extremely expensive, dangerous for the public when damaged, or extremely hard to repair, like for instance the pressure boiler of a nuclear plant or a main roller of a paper mill, more exact acceptance criteria can be taken into use. These criteria are called fitness for purpose criteria and are applied individually for the components in question.

After finding the discontinuities, here more briefly called the flaws, and after having calculated a probable speed of extension of the flaws, it enables us to stipulate the frequency of the in-service inspections that should be performed on the component in question. Hereby, the intervals are chosen in such a way that knowing the growth speed of a flaw, the following in-service inspection has to be made before a flaw has had the time to grow to an extension where there is a possibility of having a sudden failure of the component, by brittle fracture or plastic collapse, leading to vast, and consequently, expensive damages.

When deciding upon an in-service program, it is essential that the program is pro-active which here means a program that is corrected for either shorter or longer inspection intervals as a result of the experience gained while implementing the program. In practice this means the use of some kind of an RBMI i.e. a risk based maintenance and inspection program for the component, unit or plant in question. The concept of RBMI will also be dealt with in the next part of this paper.

THE ROLE OF NDT IN ENGINEERING INSURANCE

The reason that insurance companies utilise NDT is to ensure the continued safe operation of equipment, thereby reducing the risks and consequently bringing financial benefit to both the insurer and the insured. As the market mostly is soft, profitability is hard to achieve in any other way than through less major losses, whereby the role of an insurance company is to promote the use of effective loss prevention measures and for underwriters to evaluate the level of loss prevention activities and loss prevention culture a possible insurable item has.

The role of the insurer is to encourage the use of machine diagnostics and thereby to act as a catalyst for the use of cost effective loss prevention measures. It is clear that time and money resources restrict the use of every single possible diagnostic method available, and that is why the relation between the client and the insurer or the broker has to be a "win - win" relationship. The service offered by the insurance company or broker must give the client an added value and this again can strengthen the business connection between the parties. The idea for the insurer is to deeply engage in the loss prevention measures of the client and through this gain both the respect from and satisfaction of the client.

In addition to the use of NDT-methods for loss prevention, these methods are used extensively for failure analyses. To find out the root cause of a major loss is one of the most important preventive measures any industrial as well as any insurance company can take. In this search for the root cause NDT-methods are exploited extensively.

Besides the use of NDT methods for machine diagnostics, it is important to bear in mind that they are used parallel with a number of other diagnostic techniques, which also make non-visible phenomena visible. The foremost of these are vibration measurement and - analyses, thermography, oil-analyses and a number of relatively new electrical condition monitoring methods used for inspecting electrical machines and generators during use.

The diagnostic methods recommended by or required by insurance companies have to conform to specific requirements. For most inspections the operators performing the NDT-testing have to be certified by a certification body normally on a third party basis. Most industrial countries follow their own or an international scheme for certifying operators. In Europe we now use a CEN-standard and in the USA an ASNT-standard is in use. Active international standardisation is going on to get different national schemes standardised and gain mutual acceptance of certification results from different schemes. Today practically all schemes in use have three levels of NDT-testers in the six major NDT-methods explained below in more detail. Level 1 is for less demanding testing under supervision, level 2 for professional testers who are able to calibrate the equipment and able to evaluate the test results, and level 3 for the experts in the different methods who are able to write the testing specifications.

For all NDT-testing of critical machinery it is imperative that the companies use level 2 certified personnel. When critical components are tested and especially when fitness for purpose criteria are being applied, requirements on the inspection method can be stipulated and a validation of the inspection method required through a performance test. The authorities, like those in charge of pressure vessel safety, or the insurers can be the instances requiring such a validation. In a validation a performance demonstration of a testing process has to be performed and the specification used would normally be backed up by previous accreditation for the testing company.

No NDT-methods give a hundred percent probability of finding all flaws. On the contrary, all methods used give in practice results following specific POD (probability of detection) characteristics. Statistically these have to be taken into consideration when validating the methods. On site, the parallel use of more than one method greatly enhances the PODs of the inspections.

Due to restricted resources in time and money, the objects to be tested have to be picked and the testing periods set in advance. In other words an in-service testing program has to be devised. Nowadays one will encounter a lot of different concepts that has to do with the philosophy used by a firm for achieving high productivity and low ratios for work accidents, losses of production units and environmental accidents. The abbreviations used are e.g.:

-RBI	(Risk Based Inspection)
-RII	(Risk Informed Inspection)
-RBIM	(Risk Based Integrity Management)
-RBLM	(Risk Based Life Management)
-RBM	(Risk Based Management)
-RCM	(Reliability Centered Maintenance)
-RBMI	(Risk Based Maintenance and Inspection)

All of these utilise more or less an old rule called the "Pareto-rule" after the Italian mathematician and economist who first presented it at the beginning of the last century. According to this rule only 20 % of the machines of a plant cause 80 % of all the damages. When in-service testing programs are set up, this rule is taken into consideration. But before enough experience has been gained or due to the lack of loss statistics, one way of devising a program and to choosing the components to concentrate the testing efforts on, is to evaluate the components or machines according to their criticality. A typical example of this would be which of the machines in a paper mill ought to be included in the periodic vibration measurement program / 1/. Hereby points are summed for:

-criticality
-sensitivity to failure
-accessibility and environmental conditions
-machine r.p.m.
-financial value and
-machine service output.

When the same criteria for the points are applied to different machines or machinery, comparisons of the criticality can be estimated and the objects for the program chosen in an intelligent way.

Actually, one may well claim that this idea of using risk evaluation for industrial objects has been used by engineering insurers for ages. In underwriting the same ideas are taken into consideration and the idea of gathering loss statistics of major industrial losses as we for instance do in IMIA /2/, is to gain experience of the failures and to try to prevent more damage by appropriate loss prevention measures like using NDT-methods on the right objects.

INDUSTRIAL LOSS PREVENTION EXAMPLES

Turbines

A bulb-type water power plant with a horizontal rotor had been running for a year or so when crack-like indications were visually detected during shutdown. The indications were confirmed by magnetic particle testing and verified to actually extend through the material having a thickness of some 40 mm by using penetrant testing. The loss could have been prohibited if the welds had been NDT-tested before the final stage of welding.

When the trend in vibration behaviour for a steam or a gas turbine changes all of a sudden, a short shutdown for an endoscopy should be done. In almost all cases when this is done, a damage has occurred and the situation can be viewed through the video-endoscopy and the damage evaluated for decision of an immediate repair or a repair after a given period.

One steam turbine had been shut down due to excessive vibration levels. Endoscopy showed that a wing was missing and the shroud broken in front of the wing. Luckily enough, the wing had flown out through an intermediate steam outlet without damaging any internal parts. After the machine was opened, the wing replaced and the shroud repaired by welding an extra ultrasonic inspection of the wings was performed as a proposal from the NDT-expert of the insurance company. Maintenance people at the plant had been informed that an ultrasonic inspection would not be possible due to the complicated geometry in question. The testing was done with a special probe and an incipient crack was found in the neighbour wing. It is obvious that it would have caused a major loss if it had not been found.

Boilers

Boilers of all kinds often have to be shut down due to leakages in either super-heater pipes or pipes from the convection zones due to excessive erosion or corrosion of the pipes. Most often damages like this can be avoided through an in-service program for measuring ultrasonically the remaining thicknesses of the most exposed areas. This saves many unnecessary shutdowns that require time for cooling down, which typically in a recovery boiler is fairly long, welding and test-pressurising of the boiler. When a leaking pipe has to be replaced, it is extremely important to use as much time as possible for testing the neighbouring pipes or areas in order to ensure that they are sound. In this work magnetic particle testing is used for magnetic material and penetrant testing for non-magnetic materials in addition to at least a spot checking using ultrasonic testing. When and if other flaws are then found, it is needless to say that the NDT-testing has saved considerable costs.

Lime-kilns

In the process of making pulp and paper those components of the machinery that are not doubled, tripled etc. are of course critical. If at the same time these components are hard to replace and the ordering time and consequently the replacement time is long, these would be the critical components to include in as elaborate machine diagnostic programs as possible. At a pulp mill one critical unit of this type is the lime-kiln. The lime kiln is lined on the inside with a double lining one for the thermal insulation and the other for the sake of withstanding abrasive wear. The linings may fall down in use and if this is not noticed right away, the result may be that the kiln overheats and especially the riding ring or the rollers are damaged and might develop cracking.

In one lime-kiln the lining fell down in an area. This should have been registered by the on-line thermography unit monitoring the heat of the centreline of the kiln. Unfortunately this unit did not work at the moment and the situation led to cracking of one riding ring. Using in-service inspection with magnetic particle testing and ultrasonic testing, the growth of the cracks was monitored periodically and the repair could be shifted to the shutdown period next year and thereby allowing time for the huge riding ring to be ordered, manufactured, tested and transported to the site. The order time for the riding ring was nine months.

Another lime-kiln was monitored for roller function by utilising several acoustic emission sensors for instance for the two gear-boxes turning the kiln around. An abrupt rise in the emission activity of one of the boxes gave a warning and lead to measures for being able to dismount (pull aside) that box if it actually would break down, which it did and got internally damaged. The warning had led to going down in burning capacity of the lime-kiln and the kiln could thus be rotated uninterruptedly with only one gear-box long enough to get another gear-box assembled at the next planned stoppage of the production line.

Electrical Installations

The overloading of electrical distribution boards can lead to overheating and failure, resulting in equipment shutdown, loss of production and expensive claims for insurance companies. One means of preventing the above is to carry out an ‘on-line’ Thermographic Survey which uses a heat sensitive camera to image and accurately measure surface temperature. In the case of electrical installations, the camera, or imager, is used to detect ‘hot-spots’ which are indicative of overloading.

An example of an electrical survey concerns a large textile company operating many looms. Thermographic Imaging and Analysis of the electrical installation showed that some fuses were operating at a temperature 40°C higher than adjacent fuses. If this had gone unnoticed the fuses would have almost certainly failed resulting in an expensive business interruption claim.

Another example concerns a large manufacturer of frozen food. Thermographic Imaging identified major electrical overloading of the cold storage facility. In this example, Thermography almost certainly prevented major electrical failure which would have resulted in a loss of cold store temperature and an expensive claim for deterioration of stock.

Shell Boilers

In the UK, shell-type boilers represent 'high' risk examples of industrial plant. The likelihood of failure of a shell boiler is relatively high, with almost 20% of those subject to NDT being found to have potentially serious service-induced defects. Also, the consequence of failure can be very extreme, as the photograph illustrates. Engineering insurance companies in the UK have taken action to mitigate this risk by implementing a programme of NDT that is applied to relevant shell boilers at least once every five years. Through a trade association, the Safety Assessment Federation (SAFed), best-practice guidelines have been generated /3/ that, where used, ensure that all relevant boilers are subject to an agreed minimum scope of NDT.

Given the risk, it is important that the inspection, including NDT, of shell boilers is carried out with a sufficiently high reliability. Legislation in the UK goes some way to ensure that this is the case by placing specific legal responsibilities on the Competent Person that carries out the inspection. An example of such legislation in the UK is the Pressure Systems Safety Regulations (PSSR), 2000. Further, through the accreditation of NDT activities by the UK Accreditation Service (UKAS), the owners/operators of shell boilers can be provided with additional assurance that the standard of workmanship provided by the Competent Person is sufficiently high.

The combination of quality assurance measures, the availability of best practice guidance and a 'goal setting' legislative framework has reduced the risk associated with shell boilers to acceptable levels in the UK and has prevented significant losses.

Figure 1. The consequence of a shell boiler failure

Cranes

Cranes designed on a level luffing principle have a jib that can be raised and lowered about a pivot enabling the load to be moved in and out radially at roughly constant height. Often, the jib is controlled by a hydraulic ram acting on a luffing beam. Were this beam to fail, significant losses could result as the load would no longer be properly under control. Figure 2 illustrates the design of a quay-side crane in the UK where just such a failure of the luffing beam was experienced. The failure was deemed to have been caused by fatigue cracking at a gusset plate which eventually reduced the strength of the beam to a point where it fractured. An investigation of the failure led to the conclusion that fatigue cracking had propagated from welding flaws that were introduced during fabrication. It could also be surmised that, had a programme of effective NDT been put in place, the loss could have been prevented.

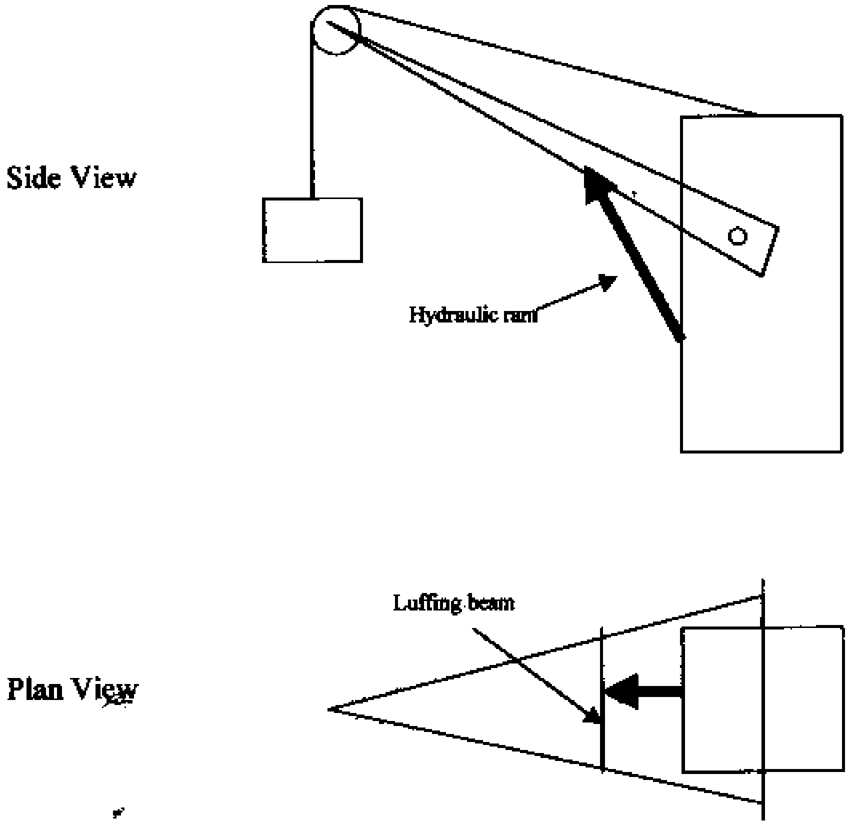

Figure 2. Schematic diagram of a Level-luffing Quay-side Crane

Figure 3 shows a tower crane that has toppled onto a building under construction. Although this particular photograph does not show it, part of the boom of the crane landed on a railway line, thereby creating a significant knock-on hazard. The loss was attributed to the failure of a hollow member that was key to the counterbalancing of the structure. The failure was caused by severe internal corrosion that could not have been detected by routine visual examination. As above, had a programme of effective NDT been put in place, the loss could have been prevented.

Figure 3. A broken tower crane. Failure caused by internal corrosion

Extrusion Presses

Extrusion presses are designed to force solid material, e.g. a pre-heated aluminium or brass billet, through a die to form a large length of extruded product. Using these machines very complex profiles can be produced, such as household window sections and door-frames.

Because of the nature of their operation, all extrusion presses are subject to eventual fatigue failure of the major structural parts; a sudden failure resulting in catastrophic equipment breakdown/shutdown, loss of production and expensive claims for insurance companies.

One means of mitigating sudden failure is to carry out NDT of the major structural parts. One of the major parts of an extrusion press are the columns or tie bars as they are sometimes called. These forged steel bars, typically three or four in total, are required to restrain the large forces between the cylinder and the front platen during a working stroke of the press. To detect any fatigue cracking in the columns, ultrasonic inspection is performed during press operation (necessary as the compressive stresses present when the press isn't running would 'close-up' any fatigue cracks making them 'transparent' to ultrasound). A good inspection regime would see the press columns inspected by ultrasonics every six months to ensure the early detection of any fatigue cracking and the prevention of sudden failure.

CONCLUSIONS AND RECOMMENDATIONS

From both underwriting and risk management point of view it is important to promote the use of machine diagnostics in general and the use of non-destructive testing in particular. The use of NDT-methods starts during manufacturing of components to machinery, plants or civil structures and continues for both for the prevention of losses and for failure analyses. None of the NDT-methods give a hundred percent probability of detection. The smaller flaws one is looking for and the more complicated the geometry of the object to be tested is, the lower the probability of detection is. By using two or more NDT-methods parallel due to the fact that they utilise different physical phenomena, the probability of detection can be enhanced considerably. The different NDT-methods are not competing with one another, they are complements to one another.

It is important to require an in-service inspection program of critical machinery to be set up and to be updated in an interactive way. When setting up the program, the objects of a machine, a plant or of a civil structure to be chosen, should be based on risk experience. In other words it is important to follow a risk based maintenance and inspection (RBMI) program. This will aim at choosing the problem areas to be tested in a cost effective way, and to use the time and money resources available for preventive testing of critical machinery. Using wrong NDT-methods or too extensive testing only diminishes the respect and appreciation for the methods. When NDT-methods are being applied, it is imperative that the testers used are certified in the method in question. In practice this means level 2 operators. For very critical testing not only the testers but also the inspection procedure need to be validated.

The appropriate use of NDT-methods brings out the invisible flaws of a structure starting from the manufacturing till the end use of the component in question. It brings added value to the insurance company or the broker who is " a mentor" for its use and acts as a catalyst for loss prevention through cost effective use of machinery diagnoses.

Appendix 1

Use of Non-Destructive Testing (NDT) in Engineering Insurance

HISTORY AND USE OF MAIN NDT-METHODS

VISUAL TESTING

An old saying defines man as "a tool-making animal". Since this is true, one can truly claim that visual inspection is just as old as mankind. Of all NDT-methods visual testing is still the most important and the overwhelmingly most used method. Yet, interestingly enough, apart from the UK, it was the last of the six classical methods referred to below to be included in the certification schemes for operators. This addition has been made during the last five years to different internationally operated schemes in comparison with the schemes for radiography or ultrasonics that have been operable for approximately almost 30 years now.

Visual testing can be performed without the aid of instruments but of course with the aid of a good portion of experience of how a component or structural part ought to look like in an undamaged form. Visual testing is done with a number of aids starting from mirrors, microscopes, boroscopes, endoscopes and nowadays predominantly with the use of video-endoscopes. The aid mentioned last has storage capability and what previously required a series of photographs for seeing changes in form or structure, can now be done by direct comparison on the screen. Hereby trends of for instance bending or thinning of components can be seen and also measured using a light falling oblique onto the surface.

Visual testing is performed in many stages of manufacturing and assembling machinery but is also extensively used for in-service inspection of critical components. Typical examples are hot path inspections of gas turbines and vane and blade controls of steam turbines often performed through specially made endoscope openings.

RADIOGRAPHY

In 1895 Wilhelm Conrad Röntgen discovered the unknown radiation he called x-radiation and presented to the physicists of the world the first and famous radiograph of the hand of his wife with the wedding ring clearly visible. This was the beginning of x-ray medicine diagnostics and for this he was awarded the first Nobel prize in 1901. Shortly after the first medical application Röntgen started to x-ray industrial objects like his own shot-gun. Thus, he was the first to utilise non-destructive testing and to make the invisible become visible.

Nevertheless, it was to take half a century until radiography was to be used for common industrial applications. The first was x-raying of welds in pipelines and pressure vessels. This is still today one of the most important areas of application. Before the films were developed by hand, and then around 1960-1970 automatic developing was taken into use. In principle radiography has stayed much the same from the start. On the other hand we are now following the example from medicine and are on the point of starting to use digital films made up of integral sensors whereby the document is achieved in a digital form and can be processed in a number of ways like producing tomographs of objects to be tested. Furthermore, the use of on-line radioscopy is also getting common in e.g. manufacturing pipes and castings.

MAGNETIC PARTICLE TESTING

Magnetism had been known since the antique and had been utilised in the Middle Ages for making compasses. The first NDT-application of this was utilised by the Englishman S.H. Saxby in 1868 when he checked the pipes of the cannons for cracks using a compass and no external magnetisation. The external magnetisation became possible after the Danish scientist H.C. Örstedt discovered the relation between current and the magnetic field in 1819. The utilisation of this discovery would then wait for another century until the American W.E. Hooke in 1922 discovered and patented the method of magnetising objects and producing a leakage field to which iron powder would adhere and delineate cracks invisible to the unaided eye. This method relies on such a basic phenomenon that it was easy to apply and has been widely used ever since.

Today magnetic particle testing is used both directly in daylight but also in darkened surroundings in connection with fluorescent particles making indications that are then somewhat easier to find, thus enhancing the probability of detection (POD) of the method somewhat. Typical objects for magnetic particle testing are critical automotive parts, typically steering and braking components. Calculated in tested objects this is probably the most used NDT-method due to the huge number of cars produced in the world today. Furthermore, magnetic particle testing is applied successfully to such machine parts during in-service inspections that one can expect showing fatigue cracking. The method reveals also cracks under compression, which many times is the situation when machinery has been stopped for periodical inspections.

PENETRANT TESTING

Penetrant testing was actually used before magnetic particle testing but was patented a few decades later by the American A.V. de Forest in 1945. This method was formerly called "The Oil and Whiting" method and was used for testing heavy cast parts used by the huge locomotives in the beginning of the 20th century. They applied used oil having a dark pigment, i.e. containing dirt, and the whiting was simply a water-based chalk-slurry that dried out to white film and worked as the developers used today. The idea was the same as in magnetic particle testing, namely to enlarge the width of the image of a fine crack and make it visible to the unaided eye.

Today penetrant testing uses predominantly red or fluorescent penetrants and is used for surface testing of primarily non-magnetic materials. Typical applications are components of aircraft gas turbines, stainless austenitic pipes in chemical and nuclear plants.

ULTRASONIC TESTING

The basis for ultrasonic testing of materials was established when the American F.A. Firestone in 1940 achieved a patent for his invention concerning a flaw detection device. Firestone was the first then in 1942 to use this method for the sonar. He used water as media for sending sound of higher frequency than a human being can hear(> 20kHz) through the water back and forth to the bottom and by measuring the time elapsed for a pulse to travel, he could then deduce the depth of the water. The same idea can be used for any material that easily conveys longitudinal or transverse waves. Most construction materials have this ability and thus this method can be used for measuring the distance to a reflector and /or the amount of reflected energy from the discontinuity of the homogenous material. The measuring of the distance can be directly utilised for thickness measurement and the relative amount of energy in different directions can be utilised for mapping the reflector i.e. the void in the material. The method of scientifically applying ultrasound for material testing was developed in Germany by the brothers H. and J. Krautkrämer to a high extent starting in the 1950s.

Since then the ultrasonic method has gone through several phases of development and has made enormous achievements and the method still has great potentials for even further applications. The classic materials for application were cast-steel and all types of steels except austenitic steels and some cast-irons, due to their high sound absorption and anisotropic behaviour.

Today ultrasonic thickness testing for the checking of possible corrosion or erosion thinning is applied for instance at every inspection at utility outages. Welds are tested using ultrasonic testing and angle probes to be able to reach down to the root and the sides of the welds including the HAZ (Heat affected zone) where the cracking or unfusing during welding is most likely to appear. The techniques of checking complicated geometries is demanding and requires proper certification of the operators.

In a near future probes that send waves in different directions - so called phased array-probes - and the possibility of recording, processing, saving and presentation of digitalized testing results, will enhance the POD of the method and will lead to easier testing techniques. So far the ultrasound has required a contact media either a jelly or water for penetrating into the material. In the future air-bound excitation like laser excitation will enable for instance the testing of railroad tracks at high speeds.

EDDY-CURRENT TESTING

Most cracks initiate during use and also to a high extent in the manufacturing phases of a component in the surface of the structure. This is the reason why the classical surface testing methods magnetic particle testing (MT) and penetrant testing (PT) have been and still are so successful and frequently applied methods. The problem with both MT and PT is that the application of the media is cumbersome and the recording of the results is not easy to achieve. Eddy Current testing is a non contact method where the documentation is made and can be saved electrically. This method was being developed primarily in the United States at the beginning of the 20:th century. There were some useful applications like the Magna Q-equipment for sorting materials, but a working theory of the method was lacking. It was then the German F. Förster who in the 1950:ies clarified the theory for Eddy Current testing (ET) and devised the necessary formulae.

Since then ET has been successfully applied for the testing of tubes both in the production phase and also extensively as periodical testing using internal probes for in-service testing of heat exchangers. Today the techniques include weld testing especially underwater testing. Multiple element probes are to be expected in the near future with which the testing can be performed in one sweep instead of probing in several defined directions.

Appendix 2

Use of Non-Destructive Testing (NDT) in Engineering Insurance

PRINCIPLES OF MAIN NDT- METHODS

VISUAL TESTING

Visual inspection, with or without the use of optical aids, is performed with the aim of detecting surface-breaking flaws. There are a variety of optical aids available to the visual inspector ranging from simple hand-held magnifiers to specialist devices such as fibre-optic endoscopes for the inspection of restricted access areas. The capability of visual inspection is heavily dependent on the surface condition of the component and the level of lighting available.

Limitations: Fairly limited capability unless special optical aids are used. Method usually requires supplementing with other methods/techniques to confirm the presence of flaws and for sizing.

Typical Equipment Used:

- Eyes
- Optical Aids (Magnifiers, Borescopes, Fibrescopes)
- Film and Video Cameras for Recording

Figure 4. Use of a straight endoscope for checking possible valve damage

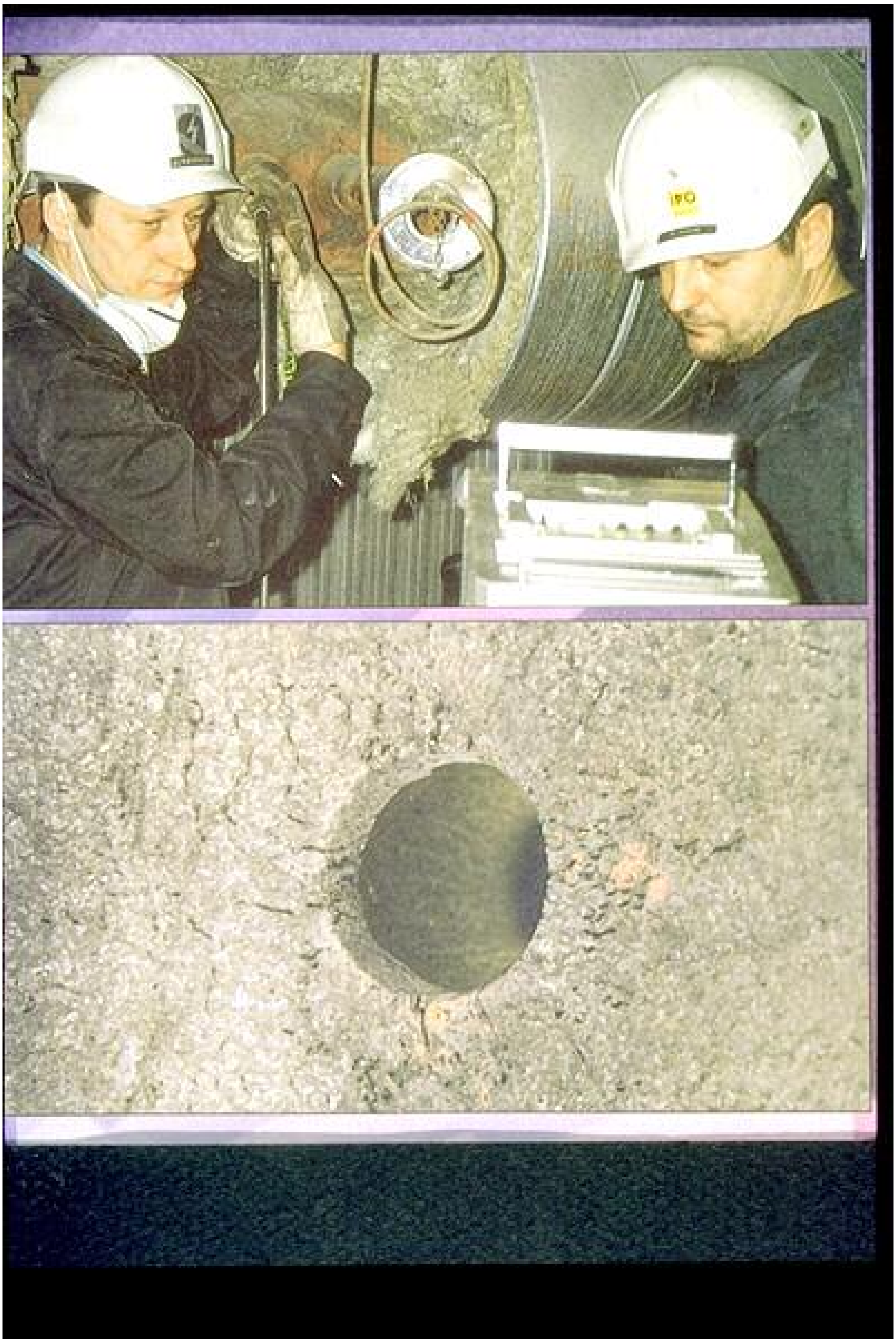

Figure 5. Endoscopy of a steam turbine via a pre-manufactured endoscopy hole

RADIOGRAPHY

In radiographic testing, a source of X or gamma radiation is used to produce an image of the component on photographic film (by placing the radiation source on one side of the component and the film on the other). Following exposure to radiation, the film is then processed and then viewed on an illuminated screen for visual interpretation of the image. Radiography gives a permanent record (the exposed film), which is a major advantage of the method, and is widely used to detect volumetric flaws (surface and internal).

X-ray equipment ranges from about 20kV to 20MV (the higher the voltage the greater the penetrating power of the radiation and the greater the thickness of component that can be tested). Gamma radiography is carried out using radioactive isotope sources (e.g. Cobalt-60, Iridium-192), and is widely used for fieldwork because of its greater portability.

Limitations: Limited capability for the detection of (planar) flaws that are not oriented parallel to the radiation beam, e.g. lack of side-wall fusion. Cannot determine flaw through-thickness dimension. For most applications internal access is required (as well as external). For on-site testing, radiation safety is a major issue.

Typical Equipment Used:

X-ray Unit/Gamma Source
Film
Processing Unit
Viewing Facility

Figure 6. X-raying of a section of a weld in a pressure vessel

MAGNETIC PARTICLE TESTING

In magnetic particle testing (MT or MPI), the component is magnetised either locally or overall. If the component is sound the magnetic flux is predominantly inside the material, if, however, there is a surface-breaking flaw, the magnetic field is distorted, causing local flux leakage around the flaw. The flux leakage is displayed, by covering the surface with very fine iron particles, usually suspended in a liquid. The particles accumulate at the regions of flux leakage revealing the flaw as a line of iron particles on the component surface.

MPI is applicable to all metals that can be magnetised. With MPI, it is important to ensure that the direction of the magnetic flux is appropriate for the flaws expected. A variety of equipment is available, the most common method of magnetisation being the application of an electromagnet (AC yoke) or in some special cases a permanent magnet to the component surface. The equipment is manually operated.

In the production of serial parts like safety parts for cars i.e. predominantly steering and braking components, semiautomatic units are employed. Hereby all the rest of the testing stages are made automatically but the inspection under ultraviolet light is at the final stage performed. manually

Limitations: Can only detect flaws in ferromagnetic materials. Can only detect surface flaws (some sub-surface capability exists with this method but detection can be unreliable). Cannot determine flaw through-thickness dimension.

Typical Equipment Used:

AC Yoke
Black Magnetic Ink
White Background Paint (UV Lamp for Fluorescent Ink)
Flux Indicators

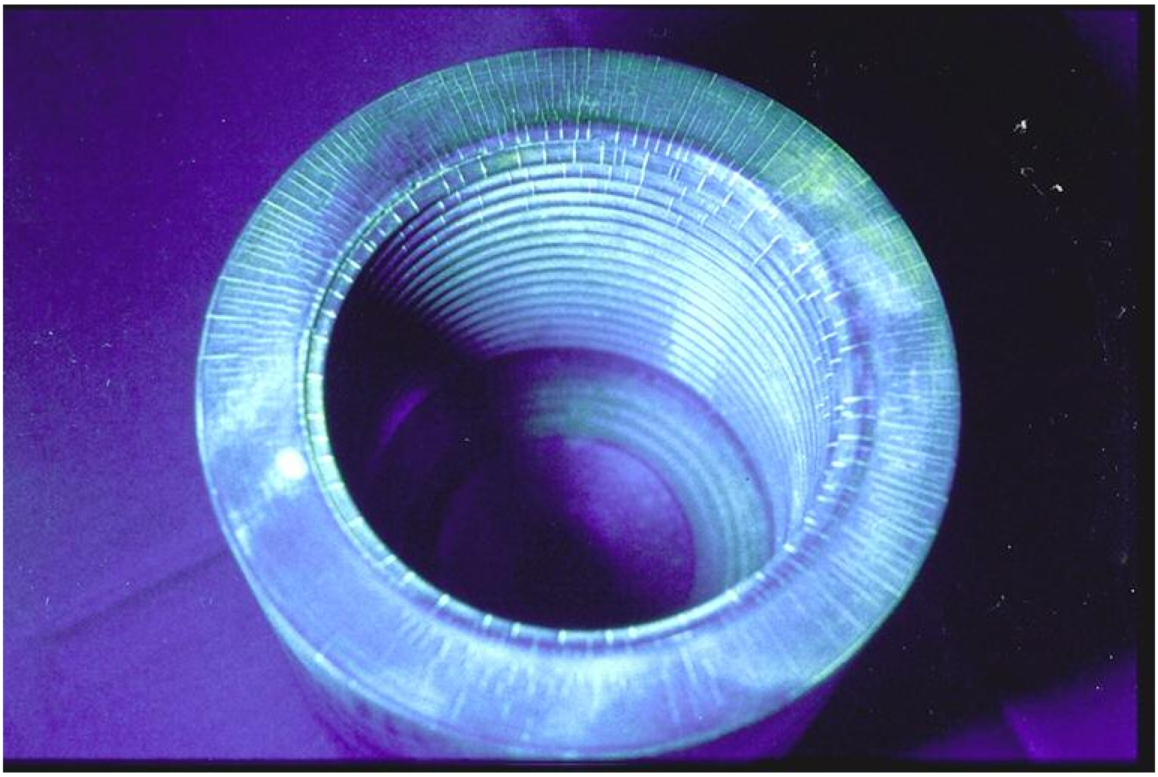

Figure 7. Nut used to join the top and bottom turbine casing of a steam turbine. Fluorescent magnetic particle testing reveals thermal fatigue cracks all over the surfaces

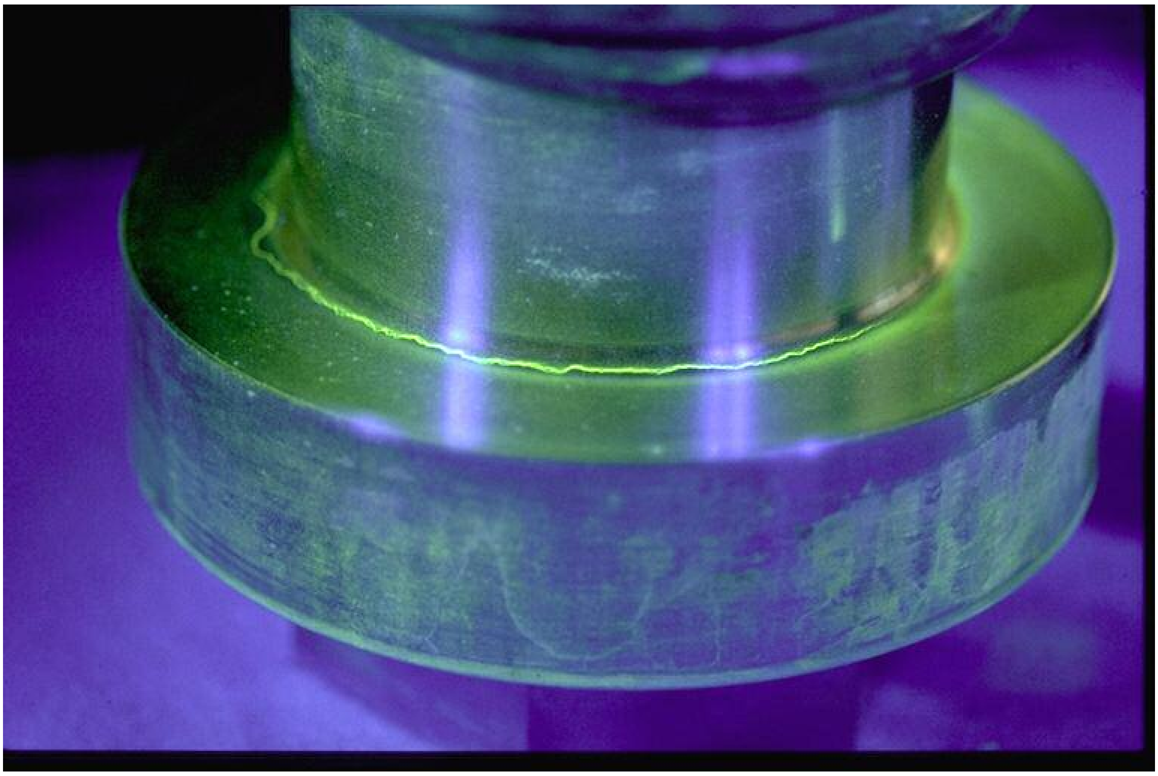

Figure 8. A 70 degree crack in a stud for an ice-breaker propeller delineated using fluorescent magnetic particle testing

Figure 9. Magnetic particle testing of a steam pipe in a power plant using a yoke and white contrast paint before applying the black suspension from a spray can

PENETRANT TESTING

In penetrant testing, liquid penetrant is drawn into surface-breaking flaws by capillary action; application of a developer draws-out the penetrant in the flaw producing an indication on the component surface. Penetrant testing is a low-cost method to apply and is very fast (large area coverage). It is usually a six stage process:

Surface cleaning
Application of penetrant to component surface
Removal of excess penetrant
Application of developer
Inspection of component surface for flaws
Post-cleaning

Penetrant testing can be applied to any non-porous clean material, metals or non-metals, but is unsuitable for dirty or very rough component surfaces. Red-dye penetrant is the most commonly used; fluorescent penetrants are used when maximum flaw sensitivity is required. Penetrant testing can be fully automated, however, in the field, the method is manually applied.

Limitations: Can only detect flaws open to the surface (the component surface on which the penetrant is applied). In addition, the flaw must not be filled with foreign material as this prevents the penetrant from entering the flaw. Cannot determine flaw through-thickness dimension.

Typical Equipment Used:

Solvent Cleaner
Red-dye Penetrant
Developer (+ UV Lamp for Fluorescent Penetrant)

Figure 10. Penetrant testing using red dye has revealed two vertical pores and a crack connecting the pores in a weld preparation of a valve

ULTRASONIC TESTING

Flaw detection

In ultrasonic flaw detection, a beam of high frequency sound (MHz range) from a small probe is used to scan the component material for flaws. This method of testing is used to detect both surface and internal flaws (planar and volumetric).

In its simplest form, a small hand-held probe connected to a flaw detector (oscilloscope) is coupled to the component surface. By scanning the probe and observing the response on the flaw detector screen (the A-scan display) the location of flaws can be determined and their size estimated. By suitable design of probe, ultrasonic beams can be introduced into the component material at almost any angle. Generally, a single probe acts as both transmitter and receiver of ultrasound, allowing inspection from one side of the component only (the single probe pulse-echo technique).

As well as this technique (the most common) there are many other techniques – tandem, through-transmission and Time of Flight Diffraction/TOFD (described in specialist NDT techniques Section 8.1.2). Most fine-grain metals can be ultrasonically tested, up-to large thicknesses, without difficulty. On the other hand, large-grain metals such as austenitic stainless steels are very difficult to inspect. Prior to their use ultrasonic systems require calibration.

With this method of testing, sensitivity to flaws can be very high. Considerable operator skill is required to interpret the A-scan displays. The majority of equipment is manually operated, however, for certain applications, complex multi-probe systems are used with computerised data acquisition/processing, display and analysis.

Thickness Gauging

The determination of component thickness using thickness gauges is described here as it is the most common field application of the ultrasonic method of testing.

Thickness gauging is a manual operation which uses a small ultrasonic probe connected to a hand-held gauge. The main use of thickness gauging is to determine remaining wall thickness particularly in component areas where corrosion/erosion is suspected. For the assessment of component condition ‘thickness surveys’, as they are often referred to, are carried out. These are usually performed by making a number of ‘spot’ measurements with the thickness gauge in a grid pattern covering the component surface or the local area of concern.

General Remark

Ultrasonic testing is one of the most powerful methods of NDT available. With this method, detection of very small flaws and accurate sizing is possible. The capability of this method to accurately determine flaw size, in particular, flaw height, makes it an integral part of fitness-for-service assessment.

Limitations: High level of operator skill required to calibrate/operate equipment and to interpret signals/results. For manual testing (and to a lesser extent for automated testing), performance capability is heavily dependent on operator skill. Weld thicknesses $< \approx 5$mm are difficult to test, as are coarse-grained structures such as those present in castings and austenitic stainless steel welds.

Typical Equipment Used:
- Ultrasonic Thickness Gauge or Ultrasonic Flaw Detector (oscilloscope type),
- Probes,
- Couplant,
- Calibration Blocks and Test Pieces

Figure 11. Ultrasonic testing of ligaments between heat-exchanger tubes


Figure 12. Ultrasonic testing for incipient cracks in steam turbine wings

EDDY-CURRENT TESTING

In eddy current testing, a coil carrying an AC current is placed close to the component surface. The current in the coil generates circulating eddy currents in the component close to the surface and these in turn affect the current in the coil by mutual induction. Surface-breaking flaws and material variations in the component affect the strength of the eddy currents. Therefore, by measuring the resultant electrical changes in the exiting coil, flaws etc. can be detected.

Eddy current testing is applicable to all electrically conducting materials. Prior to their use eddy current systems require calibration, usually on test pieces. With this method of testing, sensitivity to flaws can be very high. The equipment is manually operated.

Limitations: High level of operator skill required to interpret signals. Spurious indications can result from (i) local variations in material permeability (especially near welds), and (ii) probe lift-off (on rough surfaces). Can only really detect surface flaws (some sub-surface capability does exists but detection can be unreliable). Limited capability for determination of flaw through-thickness dimension.

Typical Equipment Used:

Eddy Current Flaw Detector (meter/oscilloscope type)
Probes
Calibration Test Pieces

Figure 13. Eddy current testing of heat exchanger tubes

The main methods explained above in more detail are in general use both in manufacturing and in-service testing. In addition to these, today there are a number of NDT and NDC methods available with easily operable applications. The main objective of the NDT-methods is to find and measure the discontinuities of various structures whereas the Non-Destructive Characterization (NDC) methods are primarily used for evaluating the condition of the material and the state of its possible degradation due to use.

As an example one may take a summer revision of a combined power plant and estimate the 20 most used machine diagnostic methods there. Then one for instance may list five other diagnostic methods and fifteen NDT- methods out of which a couple would represent NDC-methods. The most frequently used one can as an educated guess be as follows:

1. Visual testing
2. Mechanical measurements like alignment
3. Temperature measurements
4. Vibration measurements and- analyses
5. Energy efficiency measurements
6. Ultrasonic testing
7. Endoscopy
8. Magnetic particle testing
9. Oil analyses
10. Thermography
11. Eddy current testing
11. Penetrant testing
12. X-ray radiography
13. Isotope radiography
14. Layer-thickness measurements
15. Acoustic emission
16. Hardness measurements
17. Surface microscopy
18. Surface replica method
19. MFL Magnetic Field Leakage testing
20. PMI Positive Material Identification

To give an idea of the abundance of NDT- and NDC-methods available today, a list of some 70 methods is presented in the appendix 3, whereby most of these utilise different physical phenomena or effects.

Appendix 3

Use of Non-Destructive Testing (NDT) in Engineering Insurance

NDT-METHODS AND NDC-METHODS FOR MACHINE DIAGNOSTICS

1. Visual Inspection
    - 1.1 General without aid
    - 1.2 Aided inspection (mirrors, endoscopes etc.)
    - 1.3 Stroboscopic inspection
    - 1.4 Surface microscopy
    - 1.5 Video-endoscopy

2. Magnetic Particle Testing
    - 2.1 Flux magnetisation
    - 2.2 Current magnetisation

3. Penetrant testing
    - 3.1 Spot testing
    - 3.2 Immersion testing

4. Ultrasonic testing
    - 4.1 Amplitude based techniques
    - 4.1.1 Pulse echo technique
    - 4.1.2 Through transmission technique
    - 4.2 Time of flight based techniques
    - 4.2.1 TOFT Time of Flight Diffraction
    - 4.2.2 PA Phased Array techniques
    - 4.2.3 SAFT Synthetic Aperture Focussing Techniques
    - 4.2.4 EMAT Electro Magnetic Acoustic Transducer techniques
    - 4.2.5 Acoustic Holography
    - 4.3 Ultrasonic Tomography

5. Radiographic testing
    - 5.1 Film radiography
        - 5.1.1 X-ray testing
        - 5.1.2 γ-ray testing
        - 5.1.3 Accelerator testing
    - 5.2 Paper radiography
    - 5.3 Radioscopy

        5.3.1 Film radioscopy
        5.3.2 Screen radioscopy
    5.4 CRS Computed Radiography Systems (Phosphor Imaging Plates)
    5.5 XD x-ray Diffraction
    5.6 XDT x-ray Diffraction Tomography
    5.7 Neutron Diffraction

6. Eddy current testing

    6.1 Conventional (near field) techniques
    6.2 RFT Remote Field Technique

7. Temperature measurements

    7.1 Contact testing
    7.2 Contactless infrared measurement
    7.3 IT Infrared Thermography

8. Hardness measurement

    8.1 Mechanical vibration attenuation (i.e. Echotip)
    8.2 UCI Ultrasonic Contact Impedance(i.e. Krautkrämer MIC)
    8.3 TIV Through Indenter viewing (i.e. Krautkrämer TIV)

9. Layer-thickness measurements

    9.1 Magnetic pull force
    9.2 Eddy current
    9.3 □-scattering

10. PMI Positive Material Identification

    10.1 x-ray fluorescence (i.e. X-MET)
    10.2 Optical Emission Analysers (i.e. ARC-MET)
    10.3 NAA Neutron Activation Analyses

11. Crack depth measurement

    11.1 PD Potential Drop method
    11.2 ACFM AC Field Measurement

12. Metallographic replica technique (for surface examination)

13. MFL Magnetic Field Leakage testing

14. Acoustic Emission

    14.1 Loose part monitoring
    14.2 Leakage monitoring
    14.3 Crack initiation monitoring

15. Surface holography

16. Barkhausen Noise Emission

    16.1 MBN Magnetic Barkhausen Noise
    16.2 ABN Acoustic Barkhausen Noise

17. PA Positron Annihilation spectroscopy

18. Laser Shearography

19. MAE Magneto Acoustic Emission

20. NMR (or MRI) Nuclear Magnetic Resonance Imaging

21. EPR Electron Paramagnetic Resonance Microscopy (Imaging)

22. SMA Stress Induced Magnetic Anisotropy

23. FSM Field Signature Method

24. Micromagnetic analysis methods

    24.1 CM Coersitivity measurements
    24.2 MIVC Magnetically Induced Velocity Changes
    24.3 Incremental permeability measurements
    24.4 Analysis of harmonic magnetic vibrations
    24.5 Analysis of dynamic magnetostriction

25. Leak detection testing

    25.1 Vacuum techniques
    25.2 Tracer gas methods
    25.3 Bubble test methods
    25.4 Total pressure change methods

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