THE ROLE OF NDE IN THE LIFE MANAGEMENT OF STEAM TURBINE ROTORS

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Abstract: The rotors of steam turbines are subject to life limitations due to creep and thermal fatigue. Creep occurs during steady state operation due to the centrifugal stresses sustained at high temperature while thermal fatigue arises from cyclic thermal stresses set up during start up and shutdown. The most serious threat to the safety of these rotors arises from the possibility that, near the bore, creep cracks may initiate and grow to a size which could result in a brittle fracture of the rotor during a cold start. Initiation may be assisted by any pre-existing forging defects in the near bore region and growth may be assisted by fatigue due to the thermal and mechanical stresses applied during starting.

Creep cracking can also occur at blade root fixings leading eventually to the loss of blades and possibly substantial consequential damage to the turbine. Creep, thermal fatigue, and additionally stress corrosion cracking can occur at other stress concentrating features, such as balance holes and changes of section; the effect of any cracking at such features is dependant upon the local stress levels.

The detection, classification and sizing of flaws is therefore critical to life extension of Steam Turbine Rotors.

Introduction: Since the early 1970's, the continued improvement of inspection technology, in particular the ability to detect and size smaller flaws, has led to major changes in the way inspections are viewed. The concurrent emergence of the discipline of fracture mechanics, and research into crack initiation and growth rates under cyclic loading (fatigue), enables one to predict whether a crack of a given size would fail under a particular load if a particular material property or fracture toughness were known, and if flaws will propagate to failure within known time and operational factors. Utilising these tools, it is possible to accept structures containing defects, if the sizes of those defects are accurately known. This has formed the basis for the "damage tolerant" design philosophy whereby components having known defects can continue to be used as long as it can be established that those defects will not grow to a critical size that will result in catastrophic failure.

With respect to the life management of steam turbines (and other plant) RWE Innogy adopts a 'staged' approach. Stage 1 is an on paper assessment of remaining life (from running hours, hot/cold starts, temperature records, vibration history, and the utilisation of standard low cycle fatigue, creep, and rupture curves). If there are reasons to doubt the rotor has been operating as originally designed, or there have been failures in other similar rotors, this will necessitate a Stage 2 assessment. Stage 2 involves the input of NDE targeted at areas of concern, and will typically involve visual and Fluorescent MPI of the rotor surface and Ultrasonic/MPI/ECT of the rotor bore for surface and forging defects. Defect information, Strain measurements and checks on metal temperatures during transient and steady state running are fed into the calculation of expended rotor life. Crack growth for typical operating cycles, and critical crack size for severe cycles of operation are determined. If remnant life is less than the extension period for the rotor then a level III assessment is required. A level III assessment follows the same route but with increased accuracy from refined stress analysis and finite element modelling and material properties based on sampled material.

The 'input' of NDE to this approach is summarised in the flow chart (figure 1):

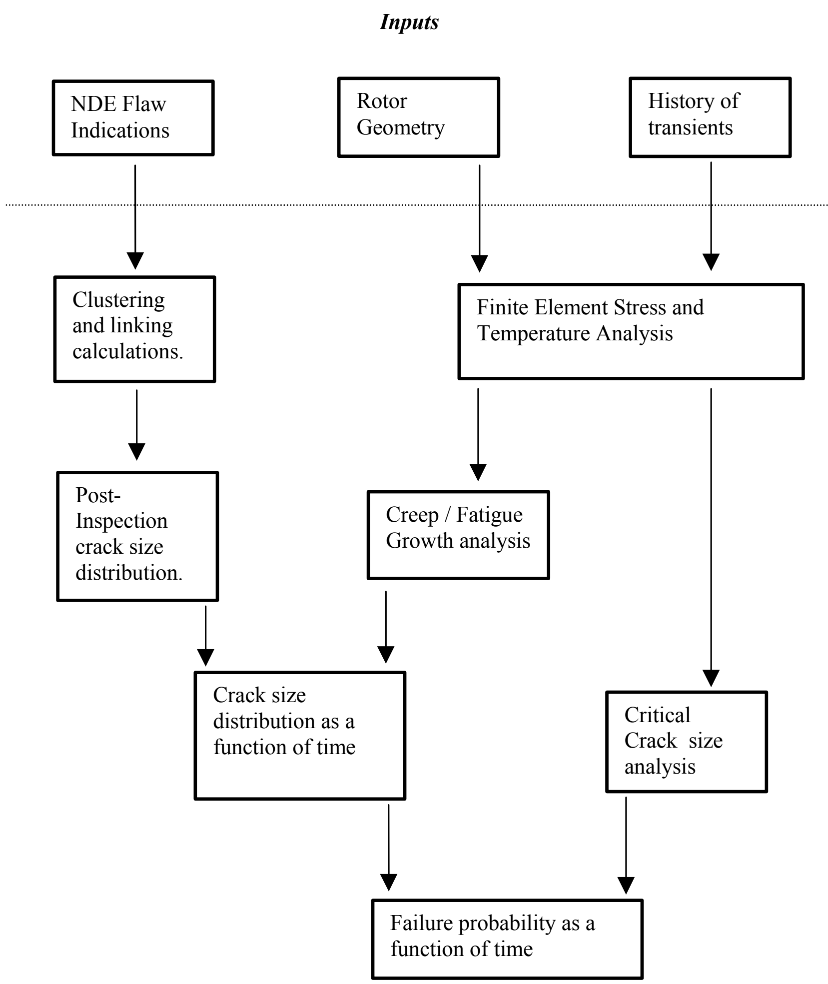

Figure 1. NDE in 'staged' approach to life management.

In practical terms, RWE Innogy fossil fuel plant and other UK operators are utilising turbines that are operating up to twice original design life in a competitive market (increased starts), and the discovery of a flaw through NDE will most likely lead to remedial engineering actions rather than any monitoring exercise. To this end, the roll of NDE in the life management of steam turbine rotors could be viewed with the emphasis on increasing the probability of defect detection during 'routine' inspections in the most cost effective manner. Furthermore, the occurrence of 'new' failures in an ageing turbine fleet, necessitate the development and validation of new techniques to detect and characterise flaws in areas of often difficult access and complex geometry. RWE Innogy have increasingly broached these issues with investment in, and validation of, automated PC based NDE techniques.

Steam Turbine Rotors And Life Limitation: A typical Rotor 'train' is shown in figure 2 containing one HP turbine, one dual flow IP turbine and three dual flow LP turbines. A train such as this will have a combined weight of over 200 Tons, and will operate at 565°C 158.6 Bar (2300psi). Turning at 3000 RPM (50Hz UK), the tip speed of a last stage LP turbine blade is upwards of 1200 Mph. The consequences of a failure on plant with such energy are severe in both human and economic terms, and the mechanisms behind such failures, as mentioned previously, have led to a science of analysis and life prediction. A detailed appraisal of this science is beyond the scope of this paper but it is important here to look at the main failure modes which bring the role of NDE into context.

The two primary modes of defect initiation and propagation in steam turbine rotors are creep and thermal fatigue. These are joined by environmentally assisted cracking and high cycle fatigue in LP rotors. For the most part (though not exclusively) areas of most concern are Creep and Thermal / Mechanical fatigue at the rotor bore, Thermal Fatigue at the rotor periphery, and recently, environmentally assisted cracking in last stage LP blading.

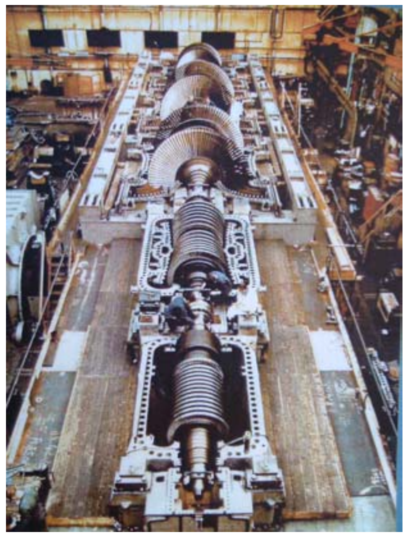

Figure 2. Steam Turbine Rotor 'train'

Rotor Bores: Older rotor forgings suffered from 'segregation' problems, whereby inclusions and impurities in the steel clustered at the centre. The centre of the forging was machined out to remove these impurities leaving the rotor 'bore'(improved de-oxidation techniques (eg.vad) have reduced the need to bore out new rotors.). The combination of thermal and centrifugal stresses during start up, and creep strain during relaxation at temperature and under steady state operation, make the rotor bore perceivably the most highly stressed area of a rotor.

During a rapid cold start the combination of high periphery and low bore temperature causes a tensile thermal hoop stress at the bore. If the combined effect of thermal and centrifugal stresses during start-up is sufficient, yielding occurs at the bore. As the rotor warms through, thermal stresses decrease and the residual compressive stress (due to previous tensile yielding) reduces bore stress to less than the normal centrifugal stress. This reduction is compensated by increased stresses at larger radii in the rotor, which are redistributed by creep during operation. With sufficient operating duration, bore stress increases to the steady state value with attendant accumulation of bore creep strain. Subsequent starts severe enough to cause bore yielding, repeat the cycle, with each cycle increasing creep rate in the rotor body slightly until the equilibrium stress distribution is restored.

The most serious threat to a rotor from the bore region arises from the possibility that, near the bore, creep cracks may initiate and grow to a size which could result in a brittle fracture of the rotor during a cold start. Initiation may be assisted by any pre-existing forging defects in the near bore region and growth may be assisted by fatigue due to the thermal and mechanical stresses mentioned above applied during start and shutdown cycles.

In assessing critical crack size, it is assumed that an initial defect will be propagated by cyclic thermal and centrifugal stresses to a final size, beyond which catastrophic brittle fracture would occur. The critical size depends on stress level, material Fracture Appearance Transition Temperature (brittle to ductile transition) and temperature in the defect region. Again, for bore defects the most arduous combination of these, as mentioned above, occurs during a cold start or overspeed test when thermal and centrifugal bore stresses are at their maximum value, whilst the rotor bore temperature (and hence material toughness and resistance to brittle fracture) is low. It is therefore important for NDE techniques to maximise the probability of detection of the smallest possible defect in the bore region (whilst maintaining economic considerations).

Thermal Fatigue: Rotor Thermal Fatigue damage describes the initiation and propagation of cracks at the rotor surface by low cycle high strain fatigue, due to cyclic thermal stressing under conditions of starting and load changing. Increasing temperature ramp rates will induce greater strain due to reduced time for temperature equalisation through the rotor body. Rotor surface thermal stresses are greatest in areas of high stress concentration and bore to periphery temperature differentials. The most arduous combination of these is found at section changes such as the heat relieve grooves of glands, fillet radii at the base of discs, and balance holes in discs where creep strain may also interact. Life management policy addresses the risk of shaft fracture due to a circumferential crack originating at the periphery, and progressing by T.F. and creep interaction to a size large enough to allow failure by mechanical high cycle fatigue (due to rotor 'self weight' cyclic bending stresses). T.F. cracks, such as those shown in Figure 3, are commonly removed by light surface machining. A reduction in stresses can be realised by increasing the radii diameter if possible. 'Depthing' of cracks such as these is particularly difficult from the rotor surface due to geometry restrictions. RWE Innogy have succesfully used Ultrasonic Time of Flight Diffraction to measure crack tips, gaining access from the rotor bore when required (see image below), however light machining usually removes most defects within 3mm of material loss. It should be noted that any access from the bore for inspection purposes is obviously negated with a solid rotor.

Figure 3. Photo showing T.F. cracking in disc radii and balance hole.

Environmentally Assisted Cracking: Environmentally assisted cracking has been of particular relevance in two catastrophic failures of last stage LP turbine blades in the past ten years. The existence of an environment that supports corrosion, notably the 'wet' nature of the steam through phase transition in the LP turbine casing, coupled with stresses encountered in blade aerofoil section changes and root fixings, can lead to the initiation of stress corrosion cracking. Add to this, potential contamination from condenser leaks, and the presence of oxygen during on start periods, and an even more aggressive environment is formed.
The photos in figures 4 and 5 are of a damaged 600 MW Turbine/Generator. The incident occurred upon start-up. One of the Low Pressure Blades (2m in length) broke off while the turbine was turning at 3000 rpm. The blade crashed through the casing (10 cm solid steel), through the roof (20 meters higher up) and landed in the HIV yard. The blade that broke took another 15 blades with it and the turbine went from 3000 rpm to standstill in a couple of seconds.

The turbine/generator shaft broke clean at two different places. The ensuing fire was so hot that some of the roof's steel beams bent. The incident happened so quickly, that the vibration monitoring equipment did not have a chance to pick anything up.
Part of the response to this incident involved the development and validation of an NDE technique to assess other similar units. Fracture mechanics calculations of critical crack depth and research on crack growth, to establish crack depth against operating hours, will determine the NDE inspection interval to ensure safe continued operation.

Figure 4. Turbine Fire

Figure 5. Broken LP Coupling

Discussion: areas of concern on rotors other than those mentioned previously include disc heads (scc and creep rupture), shrunk on disc bores (scc), differing blade root fixings (pinned, straddle, fir tree) etc. However, what is common to all the failure modes mentioned is that they are most prevalent or exacerbated during start up / shut down cycles and that frequent stop starts will decrease operating time between inspections. Changes in the UK electricity supply industry since transition from a government owned monopoly 12 years ago, have meant substantial and increasing commercial pressure for the flexible operation of large capacity utility steam turbine plant originally designed for base load operation. The implication of this is more and faster starts (up to 250/yr. for 500mw turbines) with the residual plant integrity risks from this operating regime.

Against this back drop of commercial pressure, the challenge for NDE in its role in the life management of steam turbines (and in the majority of other arenas) is to balance minimising inspection times, with maximising inspection integrity. This challenge applies to both planned outage inspection activities and reaction to failures as described earlier, and combined with the increased development of PC based inspection technology, has led a shift to automated and software driven inspection solutions.

The 'historical' approach to Rotor Bore inspections, for example, has been through a combination of visual, Magnetic Particle inspection (MPI), and Ultrasonic inspections (UT). Visual inspections are carried out utilising a direct view or video borescope. Subsequently, an MPI test conductor is positioned in the bore, and a spray nozzle containing a suspension of ferritic particles is withdrawn while a high current is passed through the conductor, attracting the ferritic particles to flux leakage sites within the bore. Viewing is then carried out using the borescope. Ultrasonic inspections utilise a probe head arrangement containing various angle probes including surface wave, mounted on a centralised rod, which is again withdrawn from the rotor bore while being articulated (often manually) to gain full coverage. The operator manually records the results of the above inspections.

The advantages of a technique which could replace this multi-stage process with a one-pass inspection, while accurately recording inspection data electronically are self explanatory (reduced inspection times, reduced possibility of rotor damage, increased probability of flaw detection, smaller flaws detected, repeatability of inspections, inspection data archiving etc.). The use of eddy current inspection (ECT) has replaced MPI on much automated bore testing equipment today. RWE Innogy have invested in a system whereby an array of eddy current coils, combined in the same motorised head arrangement as the ultrasonic probes, is linked to RDTech inspection hardware/software enabling simultaneous inspection data capture of the rotor bore in one pass.

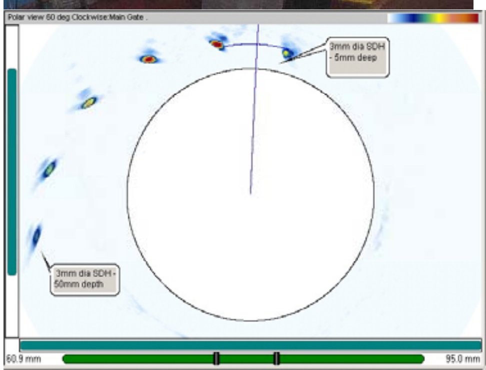

Figure 6. Bore scanning rig **Figure 7. Polar' view of test sample**

The images in figures 6 and 7 show the bore scanning rig in position on the left, and ultrasonic scanning data in 'polar' view on the right, dislaying 3mm side drilled holes from 5mm to 50mm depth.

In response to the LP blade failure highlighted earlier, RWEInnogy were directly involved in developing and validating a procedure for inspecting the 'fir tree' blade root fixings in question. The drivers behind this development were high integrity (maximum Probability of Detection (POD), electronic inspection data storage), while minimising the intrusive nature of any inspection (i.e. no need for blade removal, minimum time). The challenges involved were the tight access between blades, limited 'land' for scanning with ultrasonic probes, and the complex geometry of the fir tree fixing with the associated complexity of ultrasonic signals. These factors are replicated in many rotor inspections, and have promoted the use of phased array ultrasonics coupled with manipulation devices to aid or secure probe positioning. The images in figures 8 and 9 illustrate some of this technology with the Phoenix TRIM$_{TM}$ Turbine Rotor Inspection Manipulator set up on a test rotor disc at RWEInnogy TSG Ferrybridge workshops. Coupled with phased array ultrasonics, the system is capable of scanning a complete disc head or blade root arrangement accurately and with repeatability in minutes.

Figure 8. TRIMTM manipulator on test disc.

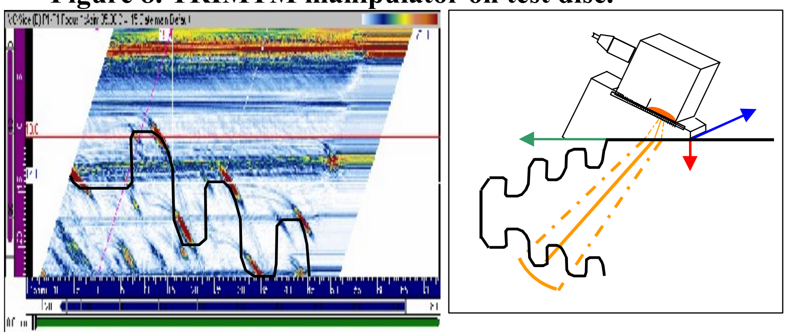

Figure 9. Electronic 'Raster' Display of 'Fir-Tree' Root Fixing and Phased array probe,

Electronic 'raster', 'sweep' , or 'skew'.

The 'fir tree' arrangement shown gives rise to a relatively complex 'A-scan' display for the manual ultrasonic operator and inspection times for an equivalent disc could be upwards of 8 hours. 'Electronic' scanning, and the ability to interrogate the ultrasonic response data with a graphic overlay of the component (as shown in Figure 9.) for example, enables increased POD over manual techniques combined with the time savings mentioned.

Conclusions: The role of NDE in the life management of steam turbines is essentially 'two-pronged'; to provide the fracture mechanics sciences with as accurate data as possible in locating and sizing initial flaws, and to respond in the same manner to the emergence of new failures on plant. In the competitive climate of the UK power industry where plant availability is paramount, this role is as important as ever in the process of optimising both operational integrity and flexible plant operation. Often, an appreciation of the role of NDE and the techniques such as those mentioned in this paper are only realised by plant operators when failure necessitates an 'emergency' response. However, the continuing development and utilisation of technologies such as phased array ultrasonics and multi-plex scanning systems, are equally as pivotal in ensuring the condition of ageing plant during planned inspection activities, with increased inspection integrity, increased efficiency, and reduced 'intrusion'.

References: Eddy current of steam turbine / generator bores. Thomas f. Murphy. GE power systems.

General Notes. RWE Innogy Plant Life Integrity.