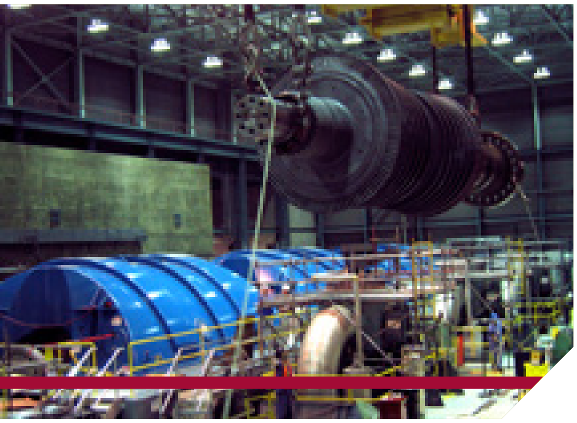
Structural Integrity Associates, Inc.®

GET REAL ABOUT THE RISKS

Does your plant have vintage rotors with early wheel materials? Structural Integrity offers new ways to manage the risks…



DO YOU HAVE BUILT-UP FOSSIL ROTORS WITH EARLY WHEEL MATERIALS?

BACKGROUND

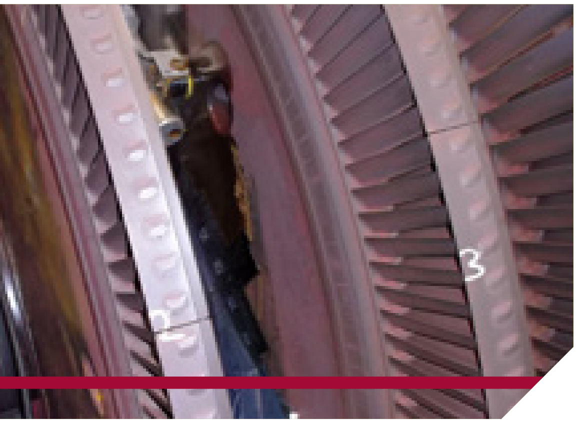
Recently an OEM of large steam turbine rotors issued a technical information letter to its fleet owners of 1950s -1960s vintage rotors with shrunk-on wheels. The OEM is concerned that <u>some</u> of the shrunk-on wheels <u>may</u> have poor material properties, such that the critical crack size for these wheels <u>may</u> be undetectable with standard ultrasonic inspection techniques. The OEM suggest the following:

1. Buying new wheels or a new mono-block rotor from them to mitigate the problem.
2. The primary crack mechanism is stress corrosion cracking, with lower probability association with low cycle fatigue and even possibly creep rupture.
3. The longevity of any specific disk is a function of the crack growth rate, the critical value of crack tip stress intensity (fracture toughness), and the applied stress.

CRACK INITIATION AND GROWTH

Looking first at crack initiation and growth mechanisms, typical mechanisms experienced in the power plant can be broadly classified as either age-driven or event-driven. Age-driven mechanisms involve processes that are active and ongoing over the life of the component and include such mechanisms as wear, creep, temper embrittlement, and others. Event-driven mechanisms include those that occur only when the component experiences the driving event and which otherwise can operate without incident. Low cycle fatigue (LCF) is generally considered to be event-driven in that damage only occurs on the occasion of the cycle. Although LCF is related to age, as cycles continue to accumulate with continued operation, it is still the event that dominates and the actual age of the component is not a consideration. Stress corrosion cracking (SCC) is also event-driven in that the exposure event(s) must occur to initiate the process.

STRESS CORROSION CRACKING

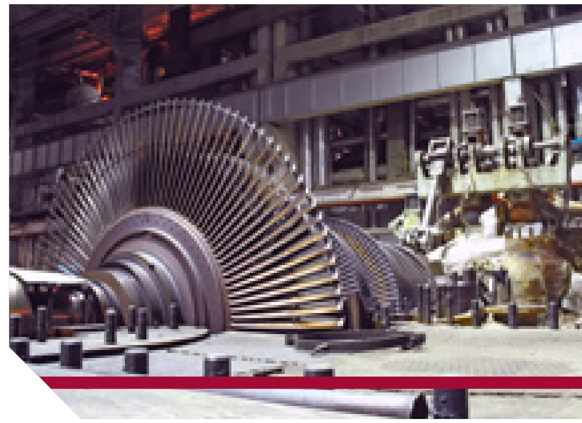


Insofar as turbine disks are concerned, SCC has long been established as the primary cracking mechanism, dating back to the 1970's when this was first discovered. For SCC to occur, certain exposure events must occur first – exposure to hostile environments under specific conditions that can be followed by a sequence of pitting, cracking, crack growth, and finally failure. The key here is that the exposure events must occur before SCC can become an issue. Typically, SCC only occurs in the disks that are downstream sufficiently that they operate in the lower temperature area of the turbine where the steam is wet, but even there only when certain chemical contaminants enter the steam. Similarly, for low cycle fatigue (LCF), a significant number of startup events must occur before a crack initiates, which typically occurs at geometric stress risers and/or pre-existing near-surface flaws. Neither of these is age-related, i.e., not operative and ongoing simply with increasing service time but related to certain events or the accumulation of certain events experienced along the way.

Creep rupture, on the other hand, is a thermal phenomenon that occurs when operating a component under stress and at high temperature above a specific temperature threshold. Another similar high temperature damage mechanism not mentioned by the OEM is that of temper embrittlement. Both of these occur over time so long as operating at the appropriate temperature and so are age-driven.

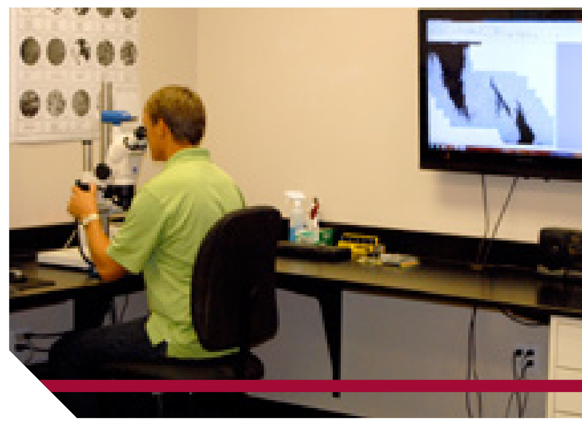
FLEET CANDIDATES

The exact population of the fleet of rotors affected by the TIL is unclear from the OEM description as is the timing of the OEM recommendations and what may have changed to warrant such a dramatic recommendation. The predominant cracking mechanisms in the subject disks are, as indicated by the OEM, stress corrosion cracking and to a lesser degree low cycle fatigue, both of which are event driven. The text appears to apply to large stream turbine rotors with shrunk-on disks, which might imply only the low pressure rotors. However, there is also discussion of high pressure and reheat turbine rotors as well, with related mention of creep rupture, which is a purely time-dependent damage mechanism. SI's recent experience indicates that the OEM has identified the affected rotors to the individual owner/operators. Regardless, all of these mechanisms can be considered in an assessment associated with the risk of continued operation of the unit.

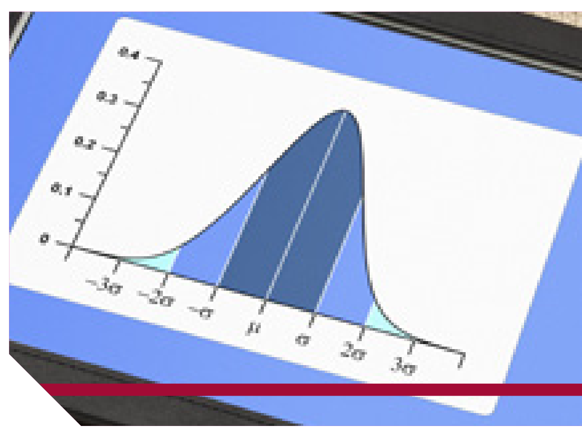


SIGNIFICANCE OF MATERIAL PROPERTIES

We know that at the time of manufacture, the material properties of the wheels would have been distributed over some range of values. Each property, assessed over a significant number of similar forgings, would have some distribution with a mean value, a maximum value, a minimum value, and an associated standard deviation. The standard deviation of a data set is a measure of spread in the data comprising the data set. For any data set, the standard deviation is a fixed value that can be determined numerically. Statistically, for similar products manufactured under similar processes, those having values near the mean are most prevalent in the distribution, with a decreasing portion of the population represented by higher and lower values with increasing deviation from the mean value. This relationship can be graphically illustrated as a classic bell curve with most of the values closer to the mean, leaving very few near the extremes.



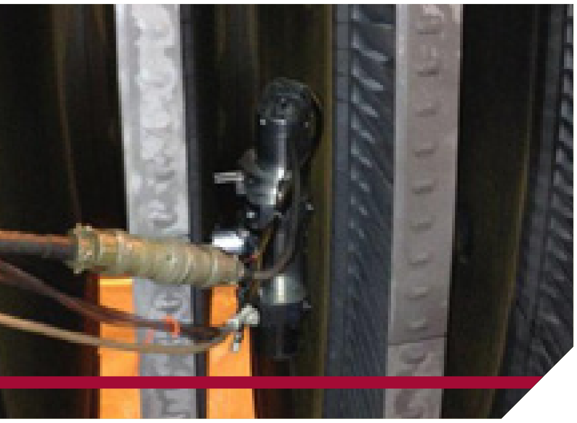
All properties should behave in a similar fashion. Much of the population should be clustered around the average, with some being "better" and others being "worse", but decreasing in number with increasing disparity from the mean. The further the value is from the mean, the fewer the number of cases exhibiting that value. Applying this idea to the vintage wheels, we would expect that there are significantly more wheels with average values than there are wheels with undesirable properties.



CRACK GROWTH AND FRACTURE TOUGHNESS

In this case, the most influential of the material properties in affecting remaining life are crack growth rate and fracture toughness, and both will behave in a fashion like that described above. However, the two are not directly linked. –There are no known correlations between crack growth rates for LCF and SCC and the fracture toughness of the material. So, crack growth rate and critical crack size must be assessed independently.

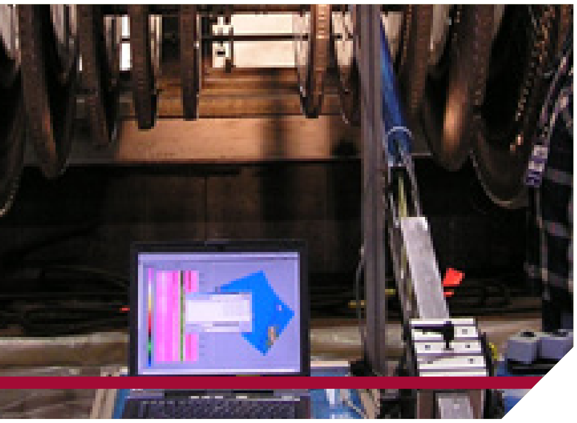
The other key variable in any assessment of remaining life is the applied stress. Low stress equates directly to slower fatigue crack growth rate and larger critical flaw size (the size of the crack at which failure occurs), and higher stress equates directly to faster fatigue crack growth and smaller critical flaw size. It is stress that defines the fatigue crack growth rate for a specific material, while it is the fracture toughness (a material property), in combination with applied stress, that defines the flaw size at which failure will occur.



Stress varies significantly from one rotor to the next, among the various shrunk-on disks for a given rotor, and within any specific disk, based on rotor (disk) size and local geometric details. So, it is important to quantify stresses for each disk and over the full volume of each, taking into account in the process any geometric discontinuities and resulting localized stress concentrations. This enables calculation of the time required to grow a crack from one size to another and to define, for specific fracture toughness, when failure will occur under the operative applied stress.

WHICH WHEELS ARE AT RISK?

We cannot disagree when the OEM states that some of the shrunk-on wheels may have poor material properties, such that the critical crack sizes for these wheels may be undetectable with standard ultrasonic inspection techniques. This, in all likelihood, is a true statement. If we couple low fracture toughness and/or fast crack growth rate with high stresses in a particular disk, there well may be a significant risk of failure, even at a relatively small crack size. However, for those disks having increased fracture toughness, and even more so those disks that see much lower stress (which has the dual impact of reducing growth rate and increasing critical flaw size), the answer may well be much different.



In the extreme, those that experience low stress in combination with high fracture toughness have an even lower risk of failure. In such cases, critical flaw size might not only be detectable, but it also may provide significant operating interval before failure must be considered a realistic possibility.

We question why this issue warrants such an extreme recommendation from the OEM. First of all, why would the owner/operator scrap a rotor and replace it with a new, fully integral (monoblock) rotor if the existing rotor is perfectly suitable for continued operation? A more conservative approach would first determine if any of the disks qualify for replacement, i.e., which might have a suitably poor combination of stress and fracture toughness to warrant replacement based on risk of failure, and then define a plan of action accordingly.

Further, the OEM recommends an alternative removal, with or without replacement of any disk that cannot be given a meaningful inspection. Because stresses vary significantly among disks and even at various locations within a disk, critical crack size is not some unique value that can be applied across the board. Rather, it is very much a function of the key properties of crack growth rate and fracture toughness and of local stress. So, we are not sure how one could even assess whether or not the inspection provided is "meaningful" without first knowing the critical flaw sizes for likely locations of crack initiation and therefore without determining first the other parameters that impact critical flaw size. Crack growth rate can be determined from the literature, but stress and fracture toughness are unique to the particular disk being assessed and must be determined on a case by case basis.

STRUCTURAL INTEGRITY ASSOCIATES' APPROACH

Structural Integrity Associates suggests that many of the built-up fossil rotors with early wheel materials can still undergo continued operation with acceptably low risk of failure, possibly providing time, while continuing to operate the turbine, to develop alternative strategies for a planned repair or replacement. It is also possible that specific turbines may have adequate future operation capacity across all of the disks to enable ongoing operation for the intended operating life of the turbine.

Correspondingly, we are prepared with another strategy to mitigate this issue. Our approach is based on sound condition assessment engineering practices that have been applied successfully for a number of years to many power plant components. In fact, we have applied our proposed approach for numerous turbine disk applications over the past several years. Our approach is risk-based and involves independent assessment of each disk. Moreover, it results in actions for cause, not comprehensive actions based purely on worst case assumptions.

STRUCTURAL INTEGRITY'S PROCESS INVOLVES FIVE STEPS:

1. **Determination of Material Properties** – The first step in assessing critical flaw size is a determination of the key material properties, specifically fracture toughness, for each disk. Crack growth rate does not appear to correlate with fracture toughness but is well established in various public domain sources, although relatively broadly distributed. However, fracture toughness must be established for each disk being analyzed. Miniature samples are removed from each disk using special tooling that slices a thin wafer of material from accessible locations on the disk. The sample removal leaves a small depression in the surface that is generally shallow enough relative to its diameter and sufficiently smooth to leave it as is, with no further conditioning required. The small sample is machined to produce a very well defined disk that then undergoes a punch test to determine certain material properties including yield strength and fracture toughness. The sample is also used to determine hardness and to assess chemical composition.

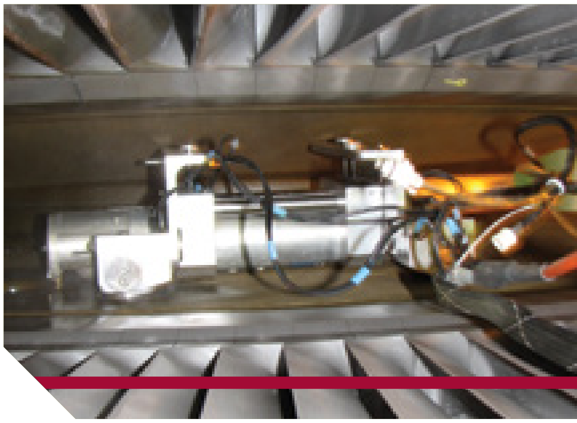
2. **Finite Element Stress Analysis** – A finite element stress analysis is performed for each disk to determine the stress profile of each. This includes consideration for mechanically and thermally induced stresses and accounts for geometric stress concentrations.

3. **Critical Flaw Size Determination** – The material properties and stresses determined via the first two steps of the process are combined to determine critical flaw sizes at various locations thought to be prone to cracking on each disk. Selected locations typically include nominal bore surface, disk sides, and significant stress riser locations.

4. **Advanced Ultrasonic Inspection** – Advanced ultrasonic inspection using phased array ultrasonic inspection techniques developed specifically for the various disk geometries and high potential crack locations will be performed to assess the presence of detectable flaws for each disk.

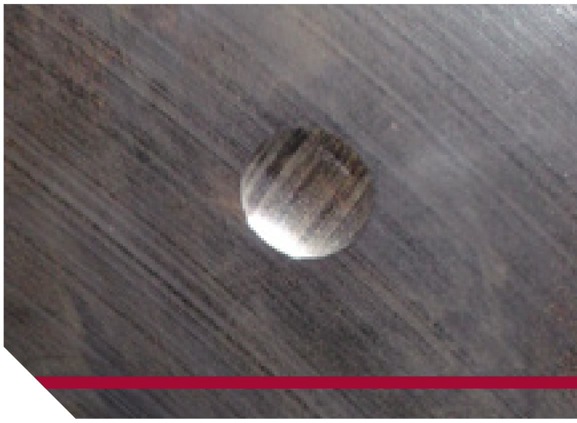
5. **Remaining Life Assessment** – A remaining life assessment will be performed based on past, current, and future (planned) operating conditions, combined with the material properties, stresses, critical flaw sizes, and NDE results from the prior four steps of the process.

Our process can be implemented using either deterministic or probabilistic methodologies. In the deterministic approach, we would typically use a conservative (high) crack growth rate from the literature, the measured fracture toughness (possibly with some added safety factor), and the calculated stresses to determine a time to failure. Because of the use of fixed, conservative values, the resulting remaining life calculation is a fixed value which is conservative. However, if the result meets the operating objective, for example, a planned reinspection interval or the planned operating lifetime of the turbine, then it is adequate.



Moving to the probabilistic analysis, this utilizes statistical inputs for the various parameters and the calculation is performed using the desired operating interval. As opposed to the deterministic analysis that provides a fixed operating interval to failure, the probabilistic approach provides a probability of failure if operated for the defined interval. The two approaches are not exclusive of each other, i.e., performing one does not preclude the other. In many cases, the more conservative deterministic analysis is performed first and the probabilistic analysis can then be performed if the more conservative analysis does not support the desired outcome.

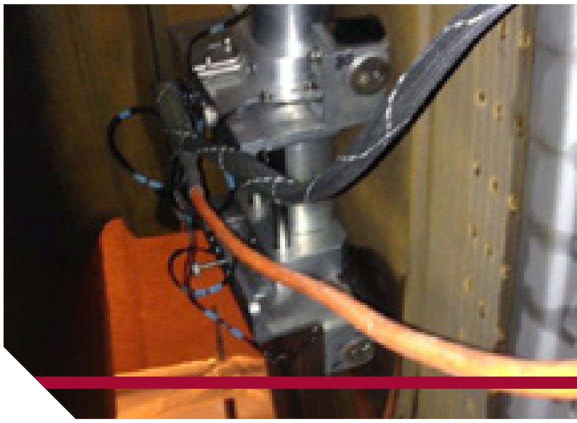
READY NOW!



Our process in its entirety is ready now for implementation. Everything needed to perform these analyses for you is in place currently, and no development is needed. In fact, these same systems and procedures have been used previously on a relatively frequent basis to perform similar studies, in fact some involving remaining life assessment of turbine rotors and disks.

Tooling for the extraction of the miniature samples was initially developed a number of years ago to support a similar program for assessing turbine and generator rotor forging in the near-bore material. More recently, we developed a miniature sampling device for sampling other than rotor bores which we routinely use for a number of applications. Miniature sample punch testing was developed by the Electric Power Research Institute (EPRI) in support of the rotor bore assessment program. EPRI has also supported condition assessment of turbine disks via, among a number of support projects addressing different aspects of disk life assessment, the development of a disk inspection test bed and implementation of an inspection performance demonstration program. Structural Integrity has participated in this demonstration, with exemplary performance well above the norm.

Contact Structural Integrity Associates to discuss an alternative strategy for your built-up fossil rotors with early wheel materials.



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