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# ADVANCEMENT IN HEATED SPIN TESTING TECHNOLOGIES

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## ABSTRACT

An ever more rapidly accelerating trend toward pursuing more efficient gas turbines pushes the engines to hotter and more arduous operating conditions. This trend drives the need for new materials, coatings and associated modeling and testing techniques required to evaluate new component design in high temperature environments and complex stress conditions.

This paper will present the recent advances in spin testing techniques that are capable of creating complex stress and thermal conditions, which more closely represent “engine like” conditions. The data from the tests will also become essential references that support the effort in Integrated Computational Materials Engineering (ICME) and in the advances in rotor design and lifing analysis models. Future innovation in aerospace products is critically depended on simultaneous engineering of material properties, product design, and manufacturing processes. ICME is an emerging discipline with an approach to design products, the materials that comprise them, and their associated materials processing methods by linking materials models at multiple scales (Structural, Macro, Meso, Micro, Nano, etc). The focus of the ICME is on the materials; understanding how processes produce material structures, how those structures give rise to material properties, and how to select and/or engineer materials for a given application [34].

The use of advanced high temperature spin testing technologies, including thermal gradient and thermo-mechanical cycling capabilities, combined with the innovative use of modern sensors and instrumentation methods, enables the examination of gas turbine discs and blades under the thermal and the mechanical loads that are more relevant to the conditions of the problematic damages occurring in modern gas turbine engines.

## NOMENCLATURE

CF: Centrifugal loading
in, ft: Inches, Feet
ID, OD: Inner Diameter, Outer Diameter
LCF, HCF: Low Cycle Fatigue, High Cycle Fatigue
RPM: Revolution per Minute
psi, ksi: Pounds per square inch, 1000psi
sec: Seconds
TMF: Thermo-Mechanical Fatigue

## INTRODUCTION

Since the conception of the first operating device, gas turbines have evolved into one of the most complex products offered in any industry. The modern world depends on gas turbines for everything from power generation to national defense. As a result, the safety and robustness of gas turbine components has been an on going field of research.

Modern gas turbine technology has come a long way from the original engines developed (independently) by Whittle and von Ohain over seven decades ago. Earlier engines packed 50hp/lb/sec (17kW/kg/sec) for each pound per second of inlet air flow; whereas modern turbofan engines are capable of producing in excess of 300hp/lb/sec (101kW/kg/sec). This improvement is the fruits of decades of innovation and advancement across a broad technology basis.

While recognizing the extraordinary accomplishments of modern gas turbines, ever complex challenges are faced by present and future gas turbine developers. The demand for more durable, efficient, quieter, and clean turbine engines continues to grow. Today’s operators of gas turbine engines demand reductions in: installation costs, operational and maintenance costs, and emissions; while improving the unit capacity, efficiency and the ability to use a broader spectrum of alternative fuels.

The demand for more efficient and robust engine cores has been an ongoing quest since the introduction of the technology. As is the case for any cyclic heat engine, the fundamental requirement in improving the thermal efficiency of an engine depends on the ability to increase the combustion temperature. The direct relationship between the operating temperature of the engine core (Turbine Inlet Temperature, TIT) and the specific core power capacity is shown in the Figure-1.

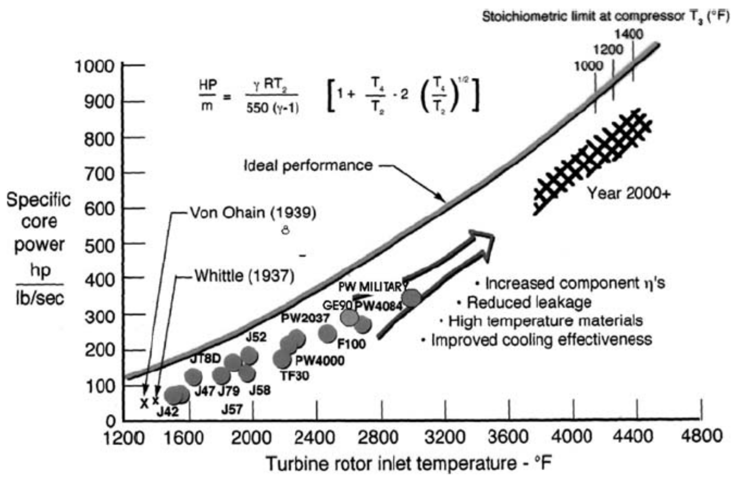



Figure-1 - Specific Core Power vs. Turbine Inlet Temperature (Courtesy of [3])

The key factors that influence gas turbine efficiency are: 1) pressure rise achieved by the compressor, 2) temperature of gas as it enters the turbine (TIT) and 3) combustor efficiency. To achieve a higher TIT the design of the combustor must be improved; followed by improvements in the designs of hot section components (combustor and turbine rotors, etc…), in order to withstand the higher temperature; and finally tuning the compressor design to achieve the optimum pressure ratio.

The main factor that limits the TIT is the temperature capability of the materials used in engineering the hot section components. Understanding the strength and damage mechanisms of the material in the elevated temperature is a critical concern.

According to studies conducted by NASA and USAF [1, 2] problems in hot section parts of gas turbine engine have a significant bearing on the operational capability of air force and civil air lines. The Department of Defense spends over $3.5 billion a year on sustaining the existing fleets, compared to $1.3 billion spent on acquiring new units. Each year it is becoming more challenging to maintain the readiness of the fleets as projected disc / rotor replacement costs increase. A lack of spare parts is already a significant problem.

Airlines world wide also face severe economic pressures. Worldwide, airlines spend $31 billion each year on scheduled maintenance, and out of that, in excess of 30% is spent on engine maintenance and of that, 70% is associated with repairs to hot section components. The study [1] concluded that a breakdown of airplane accidents in the US shows that mechanical malfunction contributes to 24% of fatal accidents and 36% of those failures are due to problems related to propulsion systems. Therefore, engine failures are the cause of roughly 8.6% of overall fatal accidents.

Significant engine hot section challenges exist today. The increasing cost of maintenance and a shortage of spare parts are driving the demand to extend the useful life of existing engine components; trend in engine core temperature increase continues as new engines are designed to be more efficient and powerful.

Developing a solution for these problems requires an improved understanding of the behavior of critical parts and the damage mechanism of the materials. A broad range of experimental and analytically focused efforts are currently being pursued by engine developers to advance this frontier. The objective of this paper is to highlight the capability of spin testing technologies that can be employed to support the validation and understanding of engine hot section components.

## WHAT IS SPIN TESTING & WHY SPIN TEST?

A spin test is a type of material and component validation method traditionally used by gas turbine manufacturers to test the effect of centrifugal load on rotating discs. An illustration of a spin test rig is shown in Figure-2.

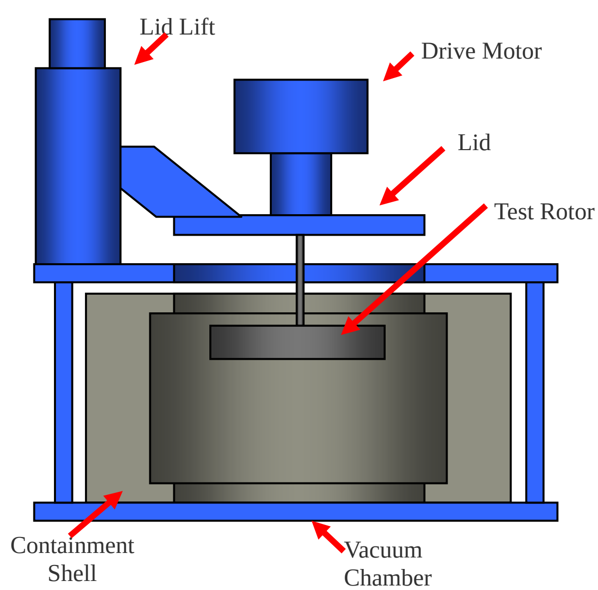


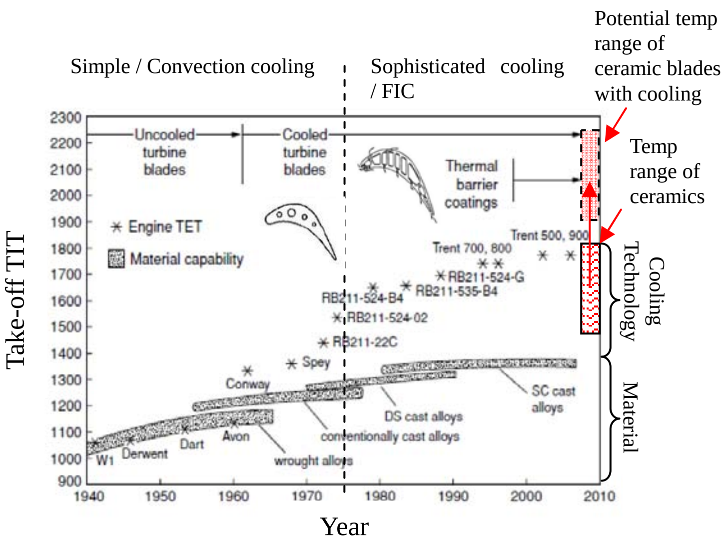

Figure-2 – Spin Test Rig

Spin testing has been employed in validating the integrity of rotors in overspeed conditions as well as confirming the resilience of fatigue life limited features of rotors [26, 27].

Typical spin test equipment (or spin rig) consists of a vacuum chamber (inc. lid), containment shell and a drive motor. Traditionally spin testing has been conducted in vacuum (<400milliTorr (<53.3Pa)) to minimize the effect of aerodynamic friction on the test rotor that can lead to undesirable temperature rise and the loss of useful drive power, which can have a significant effect on the duration and the cost of cyclic tests. For more information on spin rigs and spin testing, consult reference [28, 29, 30].

## WHY SPIN TEST?

In the gas turbine component design process, engineering of materials plays an important role in the resulting performance and safety of the final product. In a more traditional approach, material is selected from an off-the-shelf menu to design a component. The capability of the part is defined within its bound to provide a functional solution. In the design of gas turbine hot section parts, the engineering of the material itself is a key in the overall performance of the engines. This is evident in the evolutionary trend of turbine blade capability shown in Figure-3. The improvement on the overall engine performance, reflected in an increase in the Turbine Inlet Temperature (TIT), clearly depends on the evolution of better performing blade materials.




(Courtesy of [3, 5])

Figure-3 – Improvement of Turbine Blade Capabilities.

Understanding the behavior of a specific material in a final component form can be a complex problem. A machine component design is typically developed based on somewhat generic material data derived from tensile specimen tests.

While this is a perfectly reasonable approach in many engineering disciplines; for the designs of some high integrity components, such as gas turbine discs and blades, the end performance of the components can be significantly affected by the manufacturing processes and the material condition of the final product. For example, residual stresses in a turbine disc due to forging, machining and surface treatments, affects the durability of the part. Intricate turbine disc and blade geometries are also subject to complex mechanical and thermal loadings from the compound operational cycles of the machine. The nature of the loading condition has a significant influence on the damage evolution in the critical features. Such details are not easy, if not impossible, to incorporate in the design of tensile test specimens.

One of the key advantages of spin testing is that it enables assessment of rotating components in their final product form, including the shape and all the artifacts introduced on the part through the manufacturing processes. Testing a rotor in the actual assembled form also provides more accurate simulation of loadings from the interaction of individual parts in rotating environment.

Traditionally, spin tests were employed as a step to validate the design and manufacturing process of rotors near the end of the design / development process. Beyond this point, the cost, schedule and complexity of the operation leap significantly (see Figure-4). It can become extremely difficult to troubleshoot a problem in an assembled engine and the consequences of recovering from design errors discovered past the spin testing stage can be extremely unforgiving.

Traditionally, there has been a perception that devising a spin test, with comprehensive data measurements to collect useful design information, is a difficult and time consuming process. However, recent advancements in sensor technologies and spin testing methods challenge this perception and have opened the door to broader and more innovative uses of spin tests.

Modern spin testing equipment is capable of introducing a wide range of loading and environmental effects while collecting a comprehensive set of test data that can be used to improve designs. Data collected from spin tests offer direct benefits to the overall success of an engine development project. For example, disc growth data obtained from a subscale spin test disc, performed earlier in the design phase of engine development, can be used to bridge differences between the material behavior in a disc form, similar to the final product, and the tensile test data. The data can also be used to improve the damage tolerance and lifing models and reduce the risk of "surprises" later in the project.

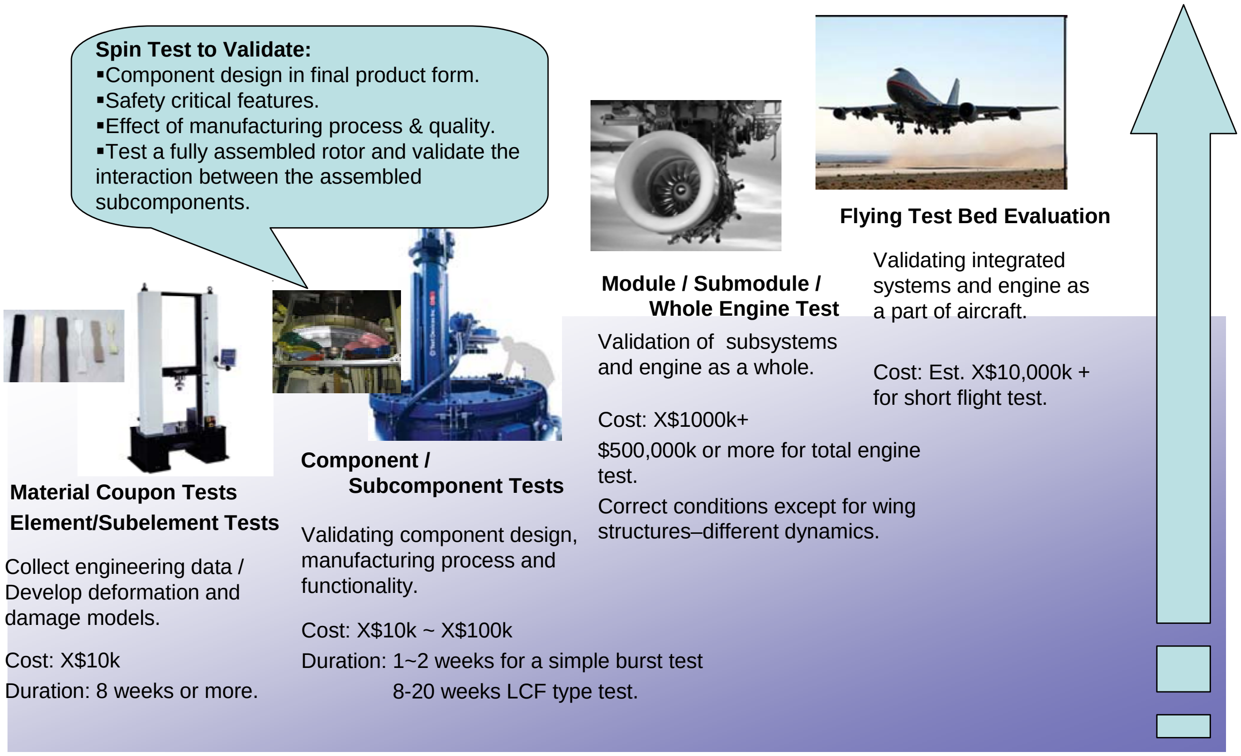



Figure-4 – Comparison of Spin Testing and Other Forms of Jet Engine Tests.

On going efforts in advancing material engineering, such as ICME (Integrated Computational Materials Engineering) may also benefit from the effective use of spin testing. Economically sized subscale disc tests can be used to study the effect of different manufacturing processes. The discs can be used to validate the engineering models of manufacturing processes and deepen the understanding of the process towards further improvement. The data from spin testing may be useful for bridging the gap between the traditional tensile specimen data and achieving a more accurate prediction of the final product performance.

Within the greater scheme of engine development, spin testing can be utilized more in the earlier phase of the project. The data from the spin testing of subscale discs may be used to generate useful material and engineering data for the development phase of an engine.

## REASONS TO SPIN TEST AT HIGH TEMPERATURE

It is a known fact that material behavior differs significantly in a high temperature environment. Figure-5 shows the temperature dependent strength data of IN718 alloy (yield and ultimate tensile strengths).

At a relatively low temperature range, the results of an ambient spin test can be extrapolated sensibly, by using tensile specimen data, to characterize the temperature dependent behavior of the material in the range. However, this approach becomes harder to justify at higher temperatures where the relationship between the material strength and temperature are no longer linearly correlated.

The hot section components of modern gas turbines operate at high temperatures close to material strength limits. At these temperatures, components are subject to heat driven microstructural damage mechanisms such as creeping, and environmental attacks from oxidation and corrosion.

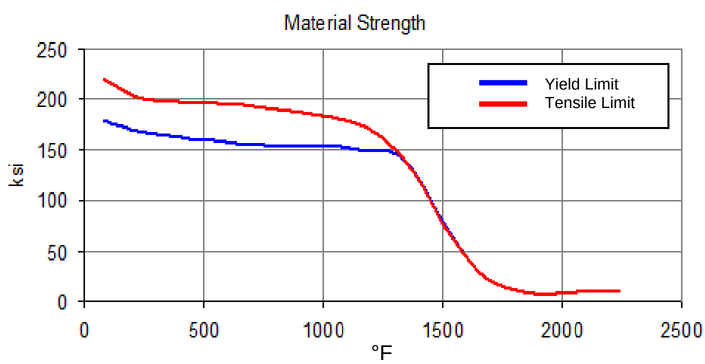



Figure-5 – Temperature Dependent Behavior of IN718 Alloy.

Creeping is a time dependent viscous plastic deformation of material at a temperature, under the influence of stress below the yield limit. Creep causes hot section parts to deform, resulting in the loss of engine performance and functionality of the components. For example, turbine blades can elongate enough to cause tips to rub the engine casing, blade can also be untwisted, and Nozzle Guide Vanes (NGV) can bow out of their original shapes and arrangements. All of these creep related issues lead to loss of engine performance and eventual failure of the machine.

Creep can exacerbate the damage and dramatically shorten the usable safe fatigue life of components. Traditionally the fatigue mechanism is understood as plasticity driven damage; however, creep can result in the formation and growth of intergranular cavities that can result in microcracks. The progression of creep damage can eventually lead to cracking and failure of components (see Figure-6).

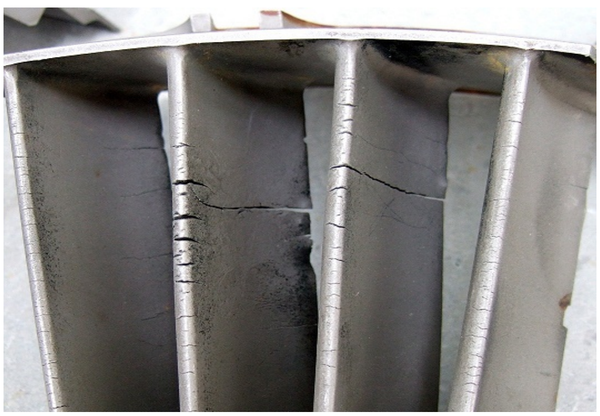


Figure-6 – Cracked and Ruptured Blade (Courtesy of [6]).

## DIFFERENT TYPES OF HIGH TEMPERATURE SPIN TESTS

### ISOTHERMAL TEST

The least complicated form of heated spin test is the iso-thermal test. A simple oven with a controlled heat source is employed to apply the heat to the test rotor. Heaters are arranged in the oven to avoid any excessive localized heating of the test rotor. The temperature of a typical metallic disc stabilizes to a saturated condition over a time in a more or less uniform distribution. In a vacuum evacuated spin test environment, the temperature distribution of a rotor, with appropriately arranged heaters, can easily achieve a stabilized temperature distribution within +/- 15°F (+/-8.3° C).

The accuracy of test temperatures depends largely on the preciseness of the temperature measurement employed. The accuracy of typical type K thermocouples used for test in a 675~1800°F (357~982°C) range is +/-3°F (+/-1.7°C). Standard precision pyrometers claim to be accurate to within 0.2% of the total measurement range. Combining the cumulative effect of sensors, instrumentation and control systems, achieving temperature accuracy better than +/-10°F (+/-5.6°C) becomes a challenge. In some cases, controlling the temperature of a spinning rotor may involve a struggle against some form of unwanted heating, such as aerodynamic heating, of a disc from the amount of air molecules remaining in the spin chamber.

An example of an iso-thermal test setup is shown in Figure-7. Typical iso-thermal oven designs feature uniformly arranged heating elements, insulation and structural shell to support its own weight.

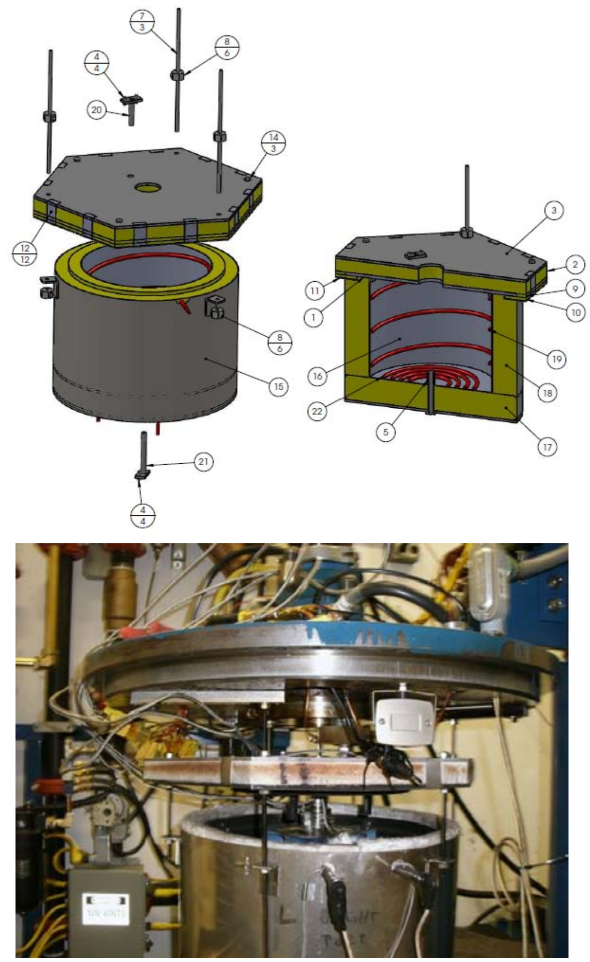


Figure-7 – An Example of Isothermal Oven.

### THERMAL GRADIENT TEST

In a real gas turbine engine, the temperature of discs and blades are not distributed uniformly. The temperature profile on a disc or a rotor assembly typically has a radial thermal gradient; hot rim to colder bore, and some axial variation (forward to aft).

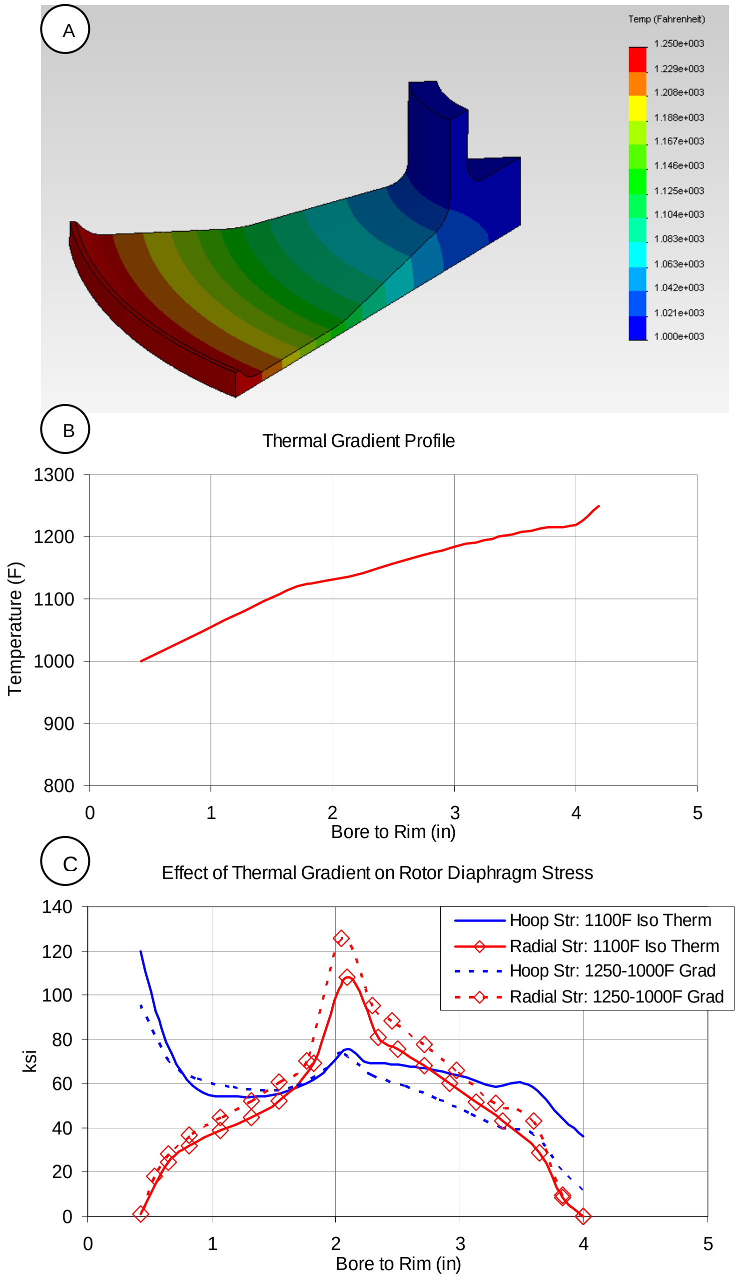



Figure-8 – The Effect of Thermal Gradient.
A) Temperature profile on the disc, B) Plot of the thermal gradient in radial direction, C) Comparison of Hoop & Radial Stresses with & without thermal gradient.

In the engine environment, along with the CF loading, the presence of a thermal gradient can be a significant source of stress in some critical features. The effect of a thermal gradient on disc stress is illustrated in Figure-8. Differences in the stress distribution in a disc were compared with and without the presence of a thermal gradient. The result shows a significant change to the level of radial stress in the diaphragm area. Also, the position of the peak stress is different in the two cases, where the disc without the thermal gradient has shown the highest stress at the bore, while the disc with the thermal gradient is stressed most at the diaphragm (i.e. location of the critical feature changed).

The difference in the ratio of hoop and radial stress (biaxiality) due to the thermal gradient also influences the evolution and damage susceptibility of the critical features to develop cracks. It is a known fact that the degree of biaxiality and triaxiality stress influences the initiation and development of microstructural damage, leading to ductile fracture or fatigue cracks [7 – 14].

An example of a thermal gradient test rig is shown in Figure-9. The system features high temperature heating sources at the rim, cooling coils at the bore and intermediate heaters in the mid-section of the test rotor area to allow trimming of the temperature profile.

Depending on the type of heat source and cooling coil design used, the design of the thermal chamber, similar to the one shown in Figure-9 has demonstrated a capability to generate 15~25°F/inch (0.59~0.98°C/mm) of thermal gradient from the rim to the bore of a disc in a vacuum environment. The temperature profile on the disc of +/10°F (+/-5.6°C) can be achieved and maintained.

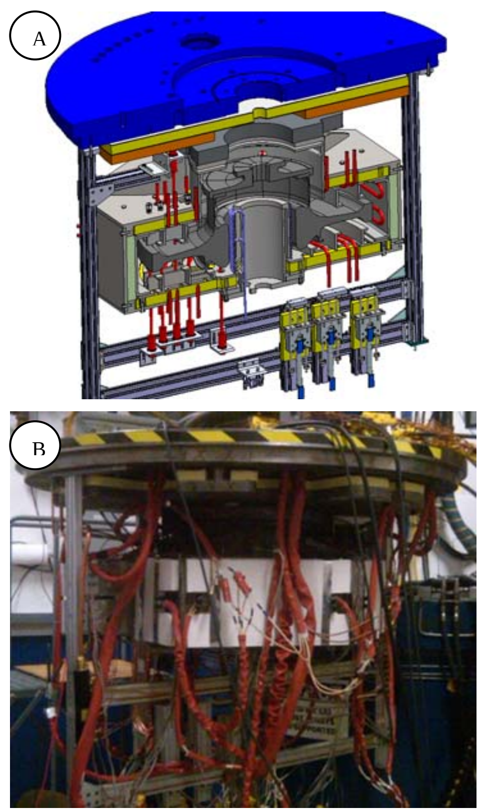



Figure-9 – Thermal Gradient Test Rig.
A) CAD model and B) Actual thermal gradient oven.

## THERMO-MECHANICAL CYCLE TEST

Cyclic loading of metallic materials at high temperature is known to cause a complex evolution of damage. In gas turbine engines, components are subjected to thermal and mechanical loading experienced in service from a combination of thermal excursions, during engine start up and shutdown, and mechanical cycles from the rotation of the components.

Thermo-Mechanical Fatigue (TMF) is a form of fatigue damage that is driven by overlaid mechanical and thermal cyclic loadings (see Figure-10). It is generally recognized that the three dominant damage mechanisms: fatigue, oxidation and creep, occur during TMF loading conditions. Most proposed models of TMF fatigue life prediction attempt to capture the effects and interactions of these factors. TMF is the primary life-limiting factor for many high temperature components in gas turbines [15 -21].

Traditionally, fatigue damage is treated as a cyclic plasticity driven, time and temperature independent damage process. Material subjected to high temperature creep undergoes viscous deformation at a constant stress level. Creep deformation leads to the formation of intergranular cavities, growth and rupture. Under a combination of thermal and mechanical cyclic loading, creep deformation contributes to the formation and propagation of microcracks.

In addition to plasticity driven fatigue and creep damage, metals exposed to high temperatures are subject to oxidation, which based on research, suggests that corrosion from oxidation is accelerated by tensile stress. During TMF, brittle oxides can enhance the nucleation and propagation of fatigue microcracks and impede the closure of crack surfaces during unloading.

The TMF rig shown in Figure-11 is capable of independently cycling both mechanical and thermal loads. Key features of the test rig include, a very intense source of heat that can be turned on and off rapidly (in this case, high power quartz infrared lamp heaters were used) and the rapid cooling of the test disc provide by a purging gas. Demonstrated temperature and speed cycles of the TMF rig are shown in Figure-12. In the test, the rim of the rotor was thermally cycled from 150°F to 800°F (66~427°C) and the bore 150°F to 280°F (66~138°C) while the speed of the rotor was cycled in-synch with the temperature. The test rig is capable of achieving a peak temperature in excess of 1000°F (538°C). The temperature in the demonstration test was achieved by merely using the half of the full power capacity of the heating system. Please refer to articles [31 & 32] for details of the TMF test rig and the demonstration test result.

The unique capability of TMF rigs can be applied to improve the understanding of the thermo-mechanical fatigue phenomena. TMF rigs allow component level studies of thermo-mechanical fatigue, where factors that drive the TMF damage process (fatigue, creep and oxidation agent) can be tightly controlled.

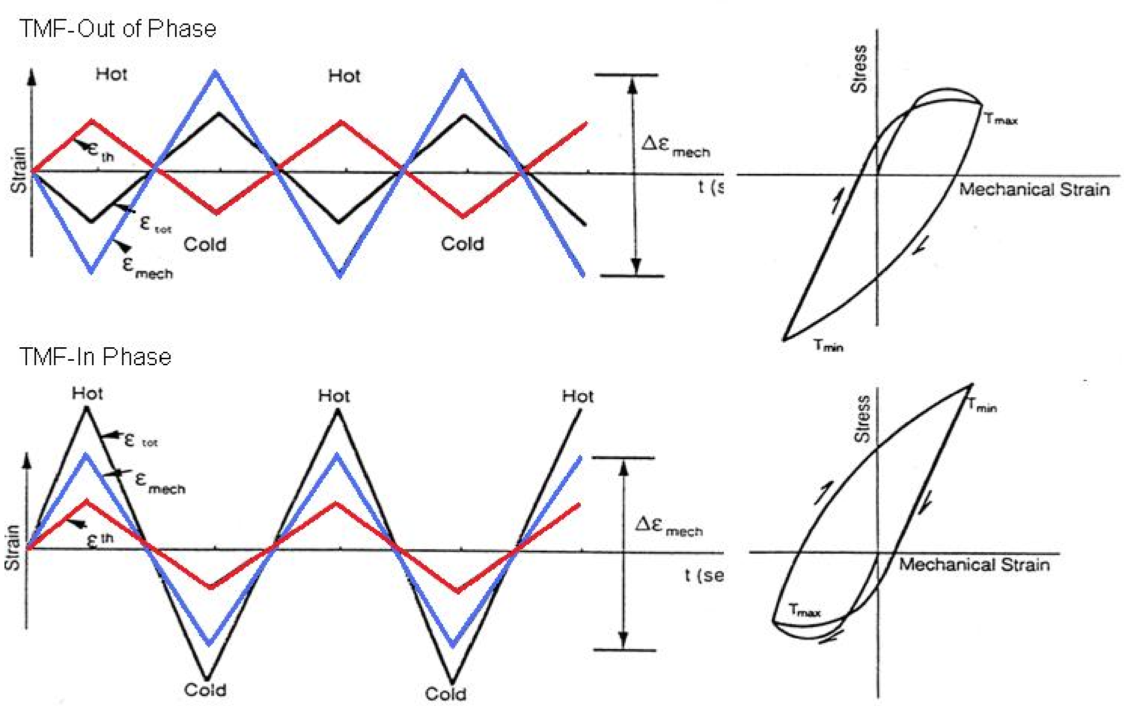



Figure-10 – TMF Cycles (Courtesy of [15]).

For example, the effect of oxidation on TMF may be studied by comparing the results of two or more separate tests; one with air (with oxygen) and the other with inert gases (without oxygen). Additionally, other corrosive elements such as sulfides may be introduced in TMF cycle.

With minor modifications, the existing TMF rig can be used to generate higher temperatures. Potentially, the rig can also be used to generate transient thermal load and employed to test the surface and subsurface damage caused by stress due to mismatch of thermal expansion rates. Examples include: damage occurring in thermal barrier coatings (TBC) of turbine blades and knife edge seals.

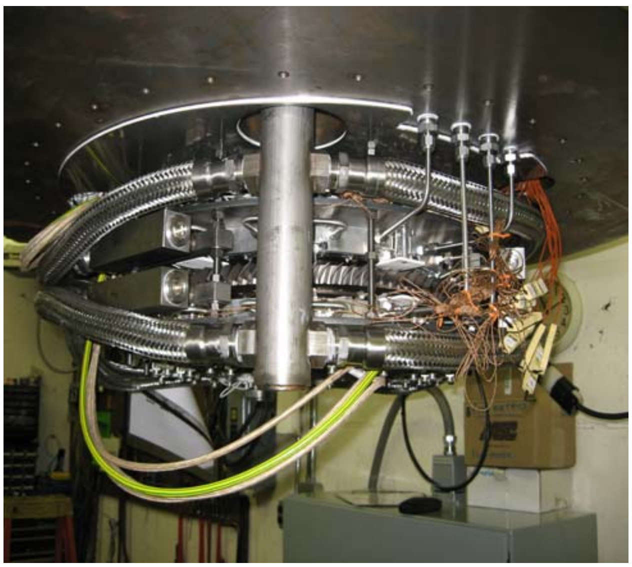


Figure-11 – TMF Rig.

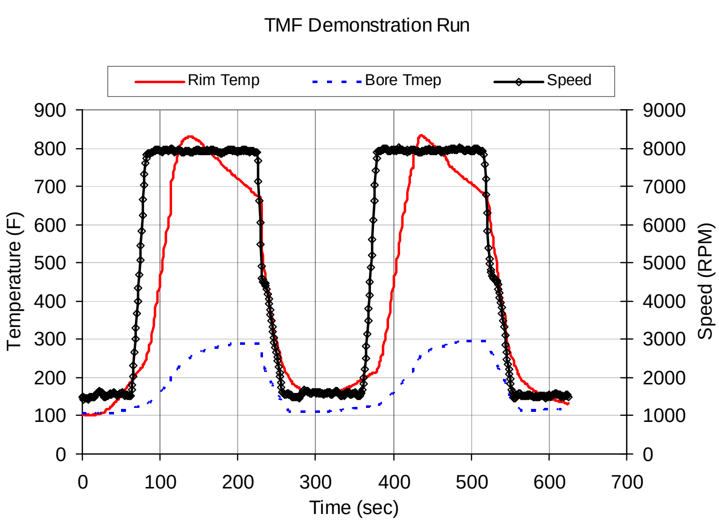



Figure-12 – TMF Rig Demonstration.

## SPIN TESTING AND DATA COLLECTION

Further to the advantages of being able to test blades and rotors in final product configuration, spin test rigs can be designed to provide greater accessibility to the test piece and enable relative ease of instrumentation. A number of new optical and none-contact sensors are available which allow in-situ real time monitoring of rotating test components. An alternative approach for testing a rotor assembly is a whole engine or engine submodule test, but these tests are significantly more difficult to design, instrument, and run. Full scale and subscale engine tests are also much more complex and difficult to troubleshoot. Recovering from an incipient problem caused by sensor failures and equipment related issues can easily grow in to a project of its own.

The advanced capabilities of spin testing and measuring technology today, offers gas turbine engineers much more data to examine the behavior of spinning rotors in greater detail than previously available. The data provides a powerful means to quantify, assess and improve their designs with increased confidence.

## ROTOR GROWTH MEASUREMENT

Figure-13 shows plots of a disc rim growth during a spin burst test. The test was conducted at an elevated temperature condition near 1000°F (538°C). The disc rim grew progressively larger as it spun to higher speeds due to the centrifugal load. The growth of the disc was monitored by an optical displacement probe system designed to measure the radial expansion of the rotor only.

The rim growth data shows a number of fascinating details of the rotor behavior during the course of the test. The initial off-set (~0.5%) in the rim growth (at 0 rpm) is a result of thermal expansion of the disc during the heat soak. The rotor was held at 5,000rpm for over three hours, and then the speed was incrementally ramped to a higher target and then dwelled at the speed for several minutes before proceeding to the next increment. The process was carried out until the disc burst.

The overall shape of the growth curve (Figure-13 (B)) shows a clear resemblance to the stress-strain relationship seen in the material tensile test data. The growth curve shows classical behavior of ductile materials, featuring linear elastic growth, the bend at the beginning of plastic growth and the accelerated growth towards burst as it approaches the strength limit of the material.

The time history of the test data shows the instance of the disc burst indicates a slight drop in speed, just before the disc blows apart (Figure-13(A)). The disc slowed down due to the accelerated expansion of the rim; due to the conservation of momentum.

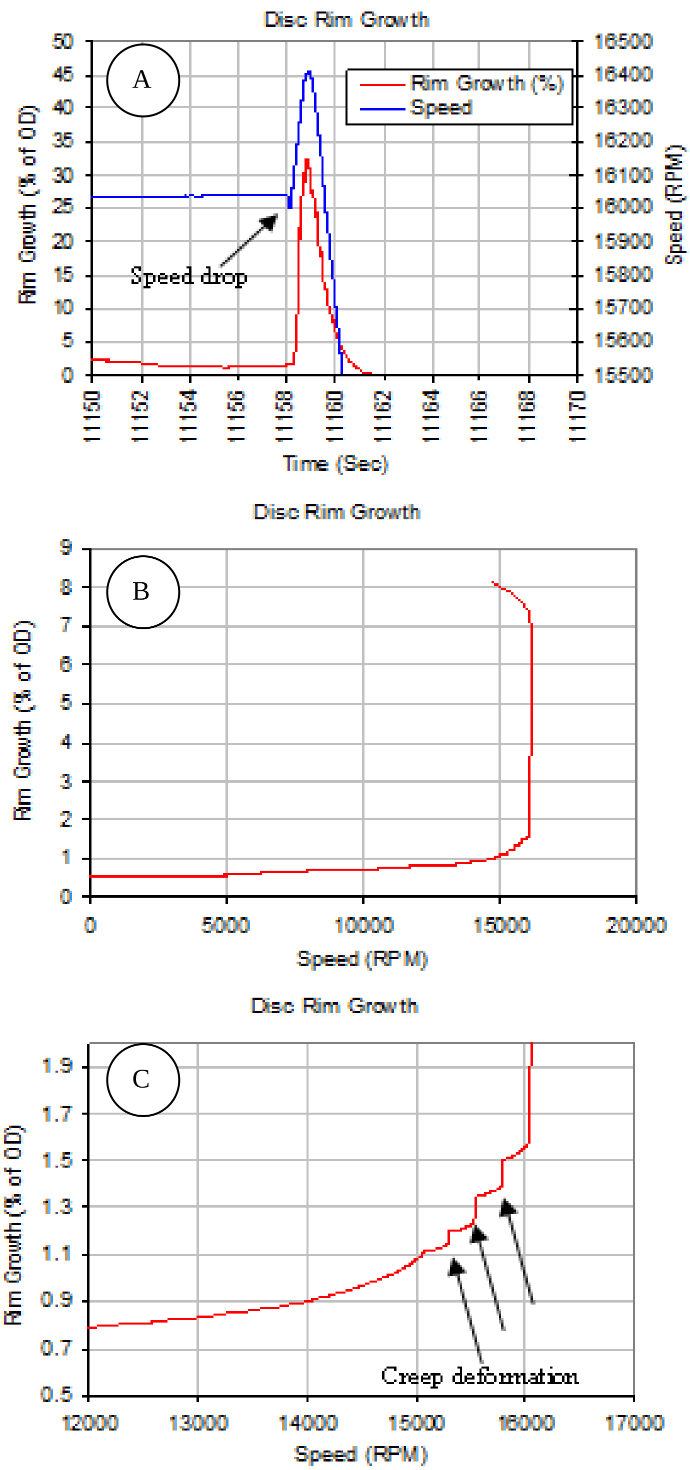



Figure-13 – Disc growth behavior towards a disc burst. A) Speed and disc rim growth at the instance of disc burst. B) Speed vs. Disc Rim Growth, C) Zoomed view of the growth curve near the knee.

An expanded view of the growth curve in the Figure-13(C) shows steps at positions when the rotor dwelled at speeds. These steps appear to signify disc growth at a constant speed, which may be related to creep damage.

## CRACK DETECTION

For almost a decade, since its inception, the Crack Detection System (CDS) has been an integral part of spin testing technique at Test Devices [21]. The technique has been used and successfully proven its effectiveness over the years on various rotors. The CDS monitors anomalous shift in imbalance vectors (namely crack parameter) to detect the presence of an emerging crack in a rotor. An example of crack detection data is shown in Figure-14. Detailed description of TDI's CDS is given in the publication [33].

The benefits of the CDS ranges from preventing catastrophic disc burst in cyclic tests to eliminating the need for interim inspections, saving a significant amount of schedule time for critical test projects. Following a disc burst, the investigative work typically takes weeks of a team of experts to evaluate the heavily deformed disc fragments and identify the location and the cause of crack initiation.

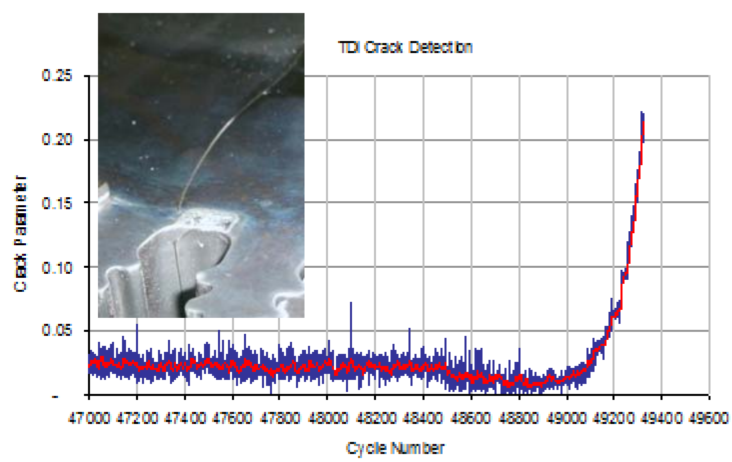



Figure-14 – A plot of crack detection data output.
A crack in the bucket groove was detected and its growth was monitored by using the crack detection system (picture: a fully developed bucket groove crack).

In a traditional spin testing, a LCF test is usually carried out to the completion of a set of predefined cycles; then rotor is disassembled and inspected prior to continuing with the next set of cycles. The process continues until the completion of the total required test cycles or until the disc bursts. The disc fragments released in a burst are often heavily deformed and smeared from impact with the containment vessel. As a result, fracture surface microstructural information is often lost. Piecing together the fragments and searching for evidences to identifying the cause and location of the crack is a daunting investigative task. Having a whole test rotor specimen with a crack(s), in the disc or blade, provides significantly more information that helps engineers and scientists to understand the cause and evolution of the damage with very high confidence.

Traditionally, maintenance schedules and a safe usage limit of gas turbine discs and blades are defined based on the crack initiation life (and the crack propagation approach for some damage tolerance type situations). The statistical nature of the lifing, and degree of uncertainty involved in defining a safe operating limit of a part, drives the tendency of the calculated life limit to be very conservative.

Improving the correlation between the size of an emerging crack and the CDS's crack indicator value has been an on going area of research interest. The allowable safe operating life of an engine disc, which would be derived from the number of cycles accumulated in the test, is often severely penalized if a disc is found to have a crack at the completion of the LCF cycle set. Gaining confidence in the capability of CDS to determine the length of a crack, in-situ, may allow lifing engineers, based on the size and growth rate obtained from CDS, to back track more exact timing of the crack initiation, and relax some of the conservatism in the existing calculation methods.

Another application of CDS is in the area of crack propagation studies. CDS has been used to aid this type of work to improve the understanding of crack propagation in rotors and blades for sometime.

Lack of spares and the increasing cost of replacement parts are becoming significant concerns. This affects the readiness of military airplanes and cost of airline businesses [1, 2]. Both military and civil operators of gas turbine engine aircrafts expressed interest in more durable designs for future engine parts as well as safely extending the useful life of existing hardware.

According to studies conducted on crack propagation, lifing methods with crack propagation may allow up to a 40% increase in the safe operating life limit compared to the crack initiation based lifing [22].

## HIGH SPEED IMAGING

Mechanical failure of components in overspeed condition, such as disc bursts and blade liberation, is driven by overloading of the material to its strength limit. Microstructurally, the damage mechanism associated with tensile overloading of the metals is described by a ductile fracture. In a ductile fracture, damage is initiated by the formation of microvoids and evolves as they grow and coalesce to form micro cracks. The formation and growth of the voids are influenced by the level of hydrostatic stress and deviatoric stress, i.e. they are influenced by the loading condition and the axiality of the critical features [9-12].

Traditionally, disc burst is treated as tensile over loading of a rotor main body (mainly hoop load). Exhaustion of ductility diminishes load carrying ability of the structure that leads to a burst of the rotor.

The rotors under overspeed condition are subject to considerable uncertainties. Under the intense centrifugal load the structures deform and the relationship between the assembled parts may change; this may vary the loading condition. The emergence of plasticity alters stress distribution in the disc and the blades; however, the interaction of plasticity and creep damage is yet to be understood. Identifying the exact location of the failure in the rotor burst is a critical step to understanding the true limitation of the bladed rotor design. In several cases, investigations of burst tests indicated that 3D features with stress concentrations, such as air holes and blade slots, may have caused discs to fail prematurely before reaching burst speeds predicted based on the gross sectional overload approach.

Stopping a test just before a disc burst or blade liberation is almost an impossible task. The condition in the structure is loaded to the limit of material strength; any instability can lead to a rapid fracture. Once it appears on a highly loaded rotor, cracks propagate at the speed of sound (65,000in/s (1651m/s) in steel); which equates to events happening in a fraction of microseconds.

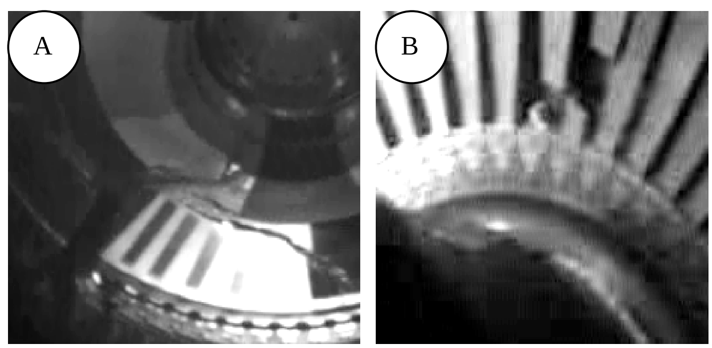



Figure-15 – High speed video images of a disc burst (a) and blade liberation at elevated temperature (b).

As explained previously, there are benefits of knowing the location of the failure initiation and the path of the damage evolution. A logical approach to capture this information in a bursting rotor or blade liberation is the use of high speed imaging (HSI). Modern HSI devices are capable of capturing images at the rate in excess of 40,000Hz; taking a picture of the event every 0.025 microseconds. An example of a disc burst event as captured on HSI is shown in Figure-15(A). The location of the crack initiation and the path of crack propagation are clearly captured.

The main challenge in capturing a rotor burst event with HSI in an elevated temperature environment is accessibility. Typically, the view of a rotor in a thermal chamber is obstructed by the surrounding insulation and oven structure. An example of the high speed imagery captured in the elevated temperature test is shown in Figure-15(B). For this application, a mechanically actuated oven was designed and implemented to capture the video stream of a blade liberation event.

## CONCLUSIONS & DISCUSSIONS

The advancement in spin testing technology offers a new approach to investigate and to improve the understanding of material behavior and the design of critical rotor features. This paper has presented a set of examples of different types of spin testing methods, with a focus on elevated temperature tests.

Improving the durability and the integrity of hot section parts holds the key to enhancing the efficiency and performance of the turbomachines. Evidences from a range of research reveal the complex and intricate nature of failure mechanisms in rotating components at high temperature.

The demand to improve the efficiency and performance of the engine continues to push the operating temperature of gas turbines higher. Materials and the designs of gas turbine components have pushed to the limit of current technology. The types of damage mechanisms involved in the high temperature environment pose ongoing challenges to gas turbine developers.

As for technological evolution, improvement and advancement of the expertise initiates from the careful observation of the phenomena and then the understanding of the event leads to the mastery of the knowledge that can be applied to derive a better design solution. Testing and data measurement is the very first step of the process.

Recent advancement in spin testing technology has opened new doors to information that was previously not available. The key advantage in spin testing is the relative ease of controlling the test environment while providing high accessibility to implement comprehensive measurement approaches, and most importantly, testing is performed on the specimens in full final product form.

The ongoing effort in ICME (Integrated Computational Materials Engineering) works to bridge the gap between the traditional engineering data and the actual performance of the final product that are subjected to various effects from the manufacturing process. The data from spin testing can provide the reference data essential in confirming the validity of the material engineering models.

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