Integration of Material-Based Simulation into Prognosis Architectures

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Abstract[1][2]— System or component prognosis can be accomplished by integrating a combination of technologies into an overall processing architecture. Key elements of this include sensed data inputs, understanding of failure physics, and variability-based life prediction techniques. Future prognosis systems will take advantage of newly developed probabilistic microstructural-based material simulation modeling for prediction of crack initiation and small crack growth of significantly smaller size than allowed by present day sensor technology. This paper presents an overview of ongoing prognosis development and how material-based modeling fits within processing architectural plans.

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1. INTRODUCTION

Systems, such as aircraft, are designed to meet overall fleet performance objectives and system maintenance planning is also designed around an overall fleet requirements. Individual fielded systems, however, are used differently or are subjected to different environmental conditions or effects. For example, consider two aircraft of the same type, and produced the same year. The conventionally used fleet maintenance schedule doesn't consider the fact that one aircraft has been flown as a warfighter in desert conditions, while the other has been used solely for training purposes. They are both maintained based on similar maintenance plans. Given these scenarios, at least 2 distinct outcome possibilities exist:

- The fleet-wide maintenance schedule used is so conservative that the warfighter performance is guaranteed and, therefore, excessive maintenance costs are expended on the trainer; or
- An "average-use" maintenance schedule is implemented resulting in excessive maintenance for the trainer and putting the success of the next warfighting mission at risk.

Given the preceding is it surprising that critical systems such as aircraft are maintained with built in conservatism? The Air Force estimates that conventional maintenance on aircraft turbine engine disks, for example, replaces 99 "good" components just to insure against the single "bad" or cracked disk in a lot of 100 (*Rasmussen et al, 2002*). The annual expenditure on Department of Defense (DOD) engine disk replacement is expected to exceed $100 million due to the fact that ever increasingly older aircraft are being flown.

Even with the execution of conservative maintenance approaches, unexpected failures occur. These are events that can't be anticipated during maintenance schedule planning. For example, it has been the case where a maintenance worker accidentally did something that resulted in impact damage to the aircraft structure. Although no significant surface damage might have been apparent and the aircraft was allowed to fly, subsurface damage could put the aircraft at flight risk. It is simply not practical to consider every possible usage event or environmental occurrence during development of fleet maintenance strategies.

2. PROGNOSIS OPPORTUNITY

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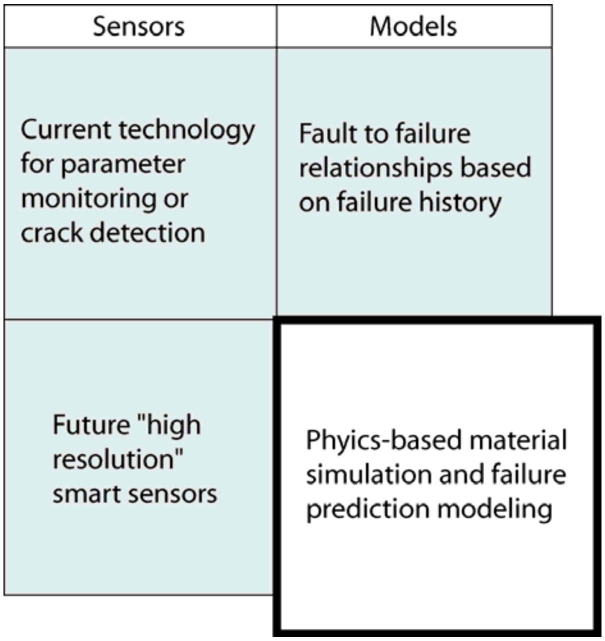
Recognizing the opportunity for significant savings and risk avoidance over conventional maintenance approaches, the DOD is investing in the development of prognosis architectures to be used onboard future systems (ie: aircraft).



Sensors	Models
Current technology for parameter monitoring or crack detection	Fault to failure relationships based on failure history
Future "high resolution" smart sensors	Phyics-based material simulation and failure prediction modeling

Figure 1. Prognosis development includes two broad categories of concentration – sensors and models.

Diagnostic approaches are routinely used onboard to highlight a fault or failure condition. For example, the landing gear locked indicator is used onboard aircraft to signal the pilot that it is safe to land. If a failure condition exists, a warning signal is sent to the pilot.

Prognosis, on the other hand, is predicting failure or failure probability BEFORE the condition actually occurs. Consider, for example, the relatively common occurrence that an automobile won’t start due to the fact that an individual gear-tooth is broken within the starter motor. Had a prognosis architecture been used onboard the vehicle, gear-tooth cracking would be predicted for future starts based on every past crank of the starter motor. Given the prediction of a gear tooth crack, the starter motor can be replaced at the driver’s convenience before the unit actually fails. As this example illustrates, prognosis readily allows for the transitioning from fleet-based to condition-based maintenance strategies. Hence, systems are assessed and maintenance is based on specific unit needs.

DOD, including Navy, Air Force, Army and DARPA, is approaching development of prognosis architectures and technologies in different ways. As shown in Figure 1, common themes center around two broad categories of development: 1) state of awareness (sensors) and 2) physics of failure (modeling). All agree that future prognosis architectures must consider both as integrated technologies.

Sensors will be used to assess the current state of the system. Although sensors such as thermocouples, strain gages, and accelerometers have been used to assess state of awareness for decades, their capabilities will be supplemented with technology allowing for miniaturization, operation in harsh environments, and remote monitoring. For example, optical sensors are used to assess and monitor crack length on structural components. However, resolution limits of 1/32 of an inch can’t measure the crack initiation state – a critical need for assessment of gas turbine blades or disks made of high strength materials. Prognosis architectures must be developed given the current state of sensor technology readiness. Equally important is that these architectures are designed with a high degree of modularity so that new sensor technology can be integrated as the current state of the art expands.

Onboard state of awareness will feed information to models designed to make failure or reliability prediction. Models will be used to predict life at subsystem or component levels as well as for the system as a whole. For example, an automobile with a cracked radiator will eventually result in failure of the cooling system as well as the entire vehicle.

Prognosis architectures are incorporating fault-to-failure prediction modeling approaches. For example, an accelerometer can be used to pick up a high vibration signal “fault” which can be translated to a remaining life prediction through physics-based modeling or simulation. In some cases fault to failure modeling approaches are limited; hence the need for the emerging material-based physics of failure modeling to be discussed next.

3. MATERIAL PROGNOSIS VISION

Prognosis architectures must consider material-based simulation and prediction approaches to supplement the capability limits of fault to failure modeling. Examples of such applicability include early stage crack initiation in critical high strength metallic components (ie: gas turbine disks, fans, blades), and for cases where mechanical induced failure occur without any prior warning (ie: electronic components).

Material-based approaches simulate the material response and cumulative degradation (ie: fatigue) as the system is used. The appropriate physics of failure methodology to be used is dependant on the material type, failure mechanisms driving degradation, and the availability of state of awareness (sensor) information. For example, VEXTEC has demonstrated material-based prognosis applicability for a turbine engine (helicopter) wheel made of titanium whose degradation can be predicted based on state of awareness for burner-outlet temperature and dwell time.

Before expanding on the details of materials-based prognosis, it will first be beneficial to present the overall vision for this prognosis application (see Figure 2).

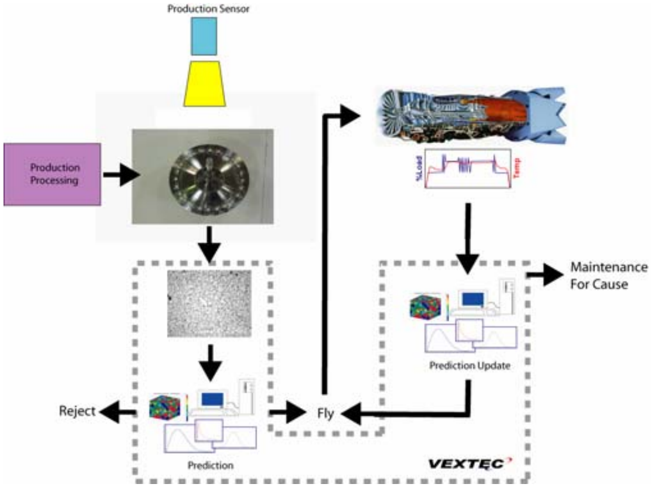


Figure 2. Material-based prognosis vision.

Manufactured components have unique variability with respect to their material properties. Components made of metallic materials exhibit variability in terms of grain structure, grain size and orientation, voids, defects, etc. This variability is a direct factor in why some components fail before others while experiencing similar usage or loadings.

Manufacturing of the future will include a microstructural characterization (ie: fingerprint) for each component. Sensors currently in development will non-destructively capture material characteristics such as grain or void information, presence of slip-bands, etc. This pristine condition or baseline (fingerprint) assessment will be forever associated with the part number or other form of component identification nomenclature.

Post-manufacture, the baseline (fingerprint) will be used within the simulation modeling approach, briefly described herein, to make an initial life prediction for the component. Research conducted by VEXTEC has indicated that pristine condition assessment about defects, grain size, and grain orientation can be used to identify life limited components within the manufactured fleet (*Tryon and Cruse, 1998*). Based on this early stage assessment, life limited components will be culled from those to be fielded.

Based on the identified, component design-unique, mechanisms causing degradation and eventual failure, the VEXTEC developed simulation-modeling approach will be tailored to accept relevant state of awareness information. Current applications are being based on the existing state-of-the-art sensors (ie: thermocouples, strain gages, etc); however, more advanced measurement devices can be used to increase prediction accuracy as the technology evolves.

As the system is used, onboard state of awareness is assessed which, in turn, serves as data input to life prediction models. The damage or degradation incurred is predicted and added to damage estimates from the past. For example, as an aircraft disk experiences its 99th flight, the degradation or damage is estimated for flight 99 and then added to the damage estimates for the previous 98 flights. Remaining useful life is the pristine or baseline estimated life (as assessed for each unique component) minus expended life (due to degradation or accumulated damage). At some pre-determined estimate of remaining useful life, the component is repaired or replaced.

This prognosis approach can be used to estimate current or future remaining useful life. Consider the example just described where damage has been assessed for the 99th mission. A remaining useful life estimate has now been made for the disk. The example scenario presumes that the pre-determined maintenance threshold has not been surpassed. Prognosis can now be used to inform the fleet commander as to whether this disk can safely be used as a warfighter or whether a less sever mission should be considered for flight 100. Based on the previously flown 98 flights, mission types are cataloged based on state of awareness readings. Before flight, simulated sensed data, based on the histogram catalog for warfighter flights, are used to predict additional degradation imposed for the anticipated flight. Hence, a damage forecast is made for flight 100 to assess whether the vehicle can be safely used as intended BEFORE the flight is actually attempted.

4. MATERIAL LIFE PREDICTION

Research has indicated that the cause of material scatter can be attributed to the inhomogeneous microstructure from which metallic materials are generally composed. To the naked eye, it appears that a metal is composed of continuous homogeneous material; however, microscopic investigation will reveal that the metal is actually composed of discontinuous inhomogeneous material consisting of a variety of individual crystalline grains, pours and defects.

The varied nature of the material microstructure causes large scatter in the fatigue behavior of metals. Discontinuities serve as potential sites for crack nucleation. When cracks are small, they grow on the order of grain size according to the properties of the surrounding grains and the growth rates typically vary. As growth occurs, the rate and behavior of the crack approaches the bulk or average properties of the material.

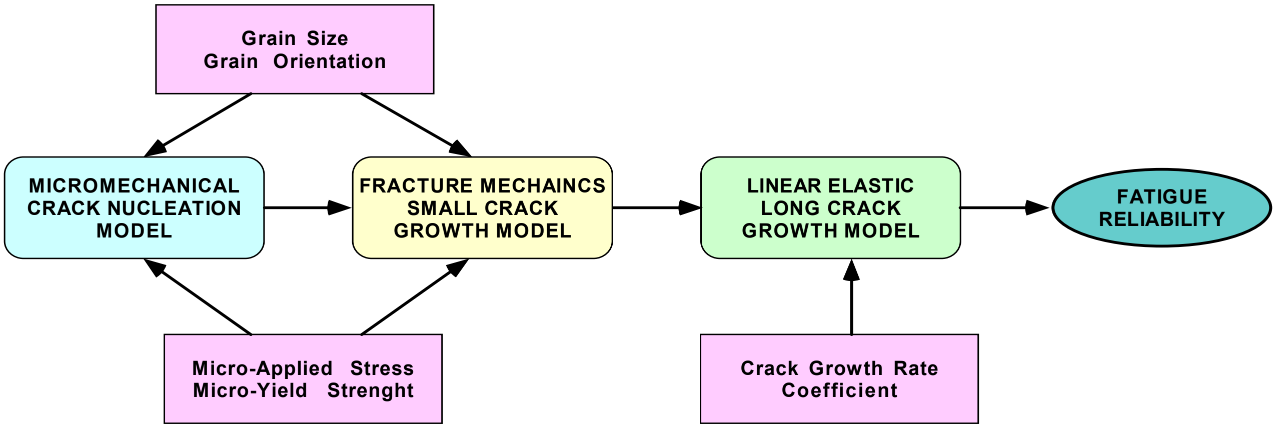


Figure 3. VEXTEC material-based fatigue model

Crack Initiation

Conventional crack initiation models are empirical in nature and based on simple macrostructural variables, which do not account for the microstructural inhomogeneity discussed previously. Traditional modeling approaches treat crack initiation as a simple parametric function of macro-stress and macro-strain variables. Often, small test specimens are cut from various component locations. The samples are cycled to a constant stress (or strain) amplitude until a load drop is noticeable or the specimen fractures. Although choice of specimen location may account for some microstructural variation, all the specimens are generally grouped together in a single test ensemble and microstructural differentiation information is lost. Conventionally, only a small amount of cyclic testing is performed (due to cost and time restraints). "Grouping" is therefore necessary in order to form the basis of a statistical confidence model. Although the conventional process is appropriate for determining component minimum fatigue properties, it can not determine site specific properties. Also, because the models are empirical, they cannot represent any condition not specifically included in the database test program.

Another problem arises when considering traditional crack initiation methods for life or maintenance prediction. During use, a component will experience mission to mission variation in the applied loadings, temperatures, etc. Although traditional crack initiation models, combined with Miner's rule or other cumulative damage models, can address this kind of variation, the models can not address variability in mission sequencing (i.e., a long mission followed by a short mission will cause different fatigue damage than a short mission followed by a long mission). Long crack propagation models can account for the sequential variation in the component usage because cycle by cycle crack extension is evaluated; however, as indicated previously, long crack propagation models are inappropriate for the vast majority of component life (*Nasser and Tryon, 2003*).

Currently prevalent crack initiation models simply relate the applied loading to the final damage. Cycle by cycle damage is not, and generally cannot be measured. It is not practical to include sequential variations in the applied stress during traditional testing (the sequence is generally unknown and the many possibilities would be too costly to evaluate). Initiation tests are generally conducted at a maximum (i.e., "worst case") stress. Worst case service condition lifing provides a lower bound for safety assurance but does not determine component reliability. As a consequence, the predicted component life will be conservative with no attempted understanding for true material behavior. Although the traditional, conservative approach is appropriate for predicting the earliest failure in the component fleet, it does not provide for an accurate prediction of life for a specific component (for which the service history is known). The vast majority of components, by definition, do not possess worst case conditions; therefore a meaningful prognostic approach for future targeted maintenance must account for site specific material microstructural properties, sequential variation in the loading and relate them to fatigue scatter.

The VEXTEC developed (patent pending) material-based prognosis method uses state of awareness (onboard) data combined with microstructural based computer software models to simulate the actual material behavior discussed previously (*Tryon, 2001*). The computer simulates many "identical" components but uses a different sample of material microstructure for each simulation. The microscopic structure of each simulated material model or "realization" for each component is properly sampled from the known or specified range of material microstructures. Each of the elements is then virtually tested to simulate real-world usage conditions. This virtual testing process is used to produce data on thousands or even millions of components in near real time.

Figure 3 shows the three levels of fatigue damage accumulation that may occur in a typical high strength component. First, a crack nucleates on a small scale on the order of the grain size. Then the crack grows as a microscopically small crack in which the crack lies in relatively few grains. Eventually the material properties, averaged along the front of the crack, approach bulk or the average material properties as the crack grows and the number of grains interrogated by the crack front increase. At this point, traditional crack growth techniques such as linear elastic fracture mechanics are used. The approach in Figure 3 addresses the evolution of micro-scale damage initiation to system level failure.

Under Air Force grant funding, microstructural-based fatigue failure models have been developed based on the observation of damage interaction with the material microstructure. For the high strength materials evaluated, interaction of the fatigue damage with the material microstructure was modeled as dislocations moving on slip planes with pinning at the grain boundaries resulting in initial defects that accommodate plastic deformation. Crack nucleation takes place when the accumulated dislocation exceeds the materials specific fracture energy. The software simulation may or may not grow the crack (i.e., crack growth may arrest depending of the size of the crack and the applied load).

The short cracks grow by emitting dislocation from the crack tips along the slip planes of the grains ahead of the short crack. The dislocation movement causes a zone of plastic deformation at the crack tip. The zone propagates freely when the crack tip is far from a grain boundary; however, as the crack tip approaches a grain boundary, the zone pins at the grain boundary. The crack may or may not grow into the next grains depending on the size of the plastic zone. The size of the plastic zone is dependent on the crack size, the applied load and the size, orientation and strength of the grains surrounding the plastic zone. The crack must be considered a short crack until the crack is of a size such that the crack tip lies in sufficient grains to assume bulk properties. Thereafter, conventional long crack growth models are used describe the growth based on linear elastic fracture mechanics.

5. SENSED MATERIAL CHARACTERISTICS

The VEXTEC prognosis approach is being developed based on the capability to direct sense specific, component unique material parameters. This is a distinct change to manner in which VEXTEC uses its modeling approach for design life prediction. For the later, variation in the microscopic substructure is addressed by modeling the grain size, grain orientation, micro-applied stress and micro-yield strength as random variables. Hence, microstructural parameters are based on fleet statistics and probabilistic forecasting. In order to accurately predict the life for a specific component, as opposed to that for the component fleet, the specific material parameters for the unique component must be considered.

Under contract to VEXTEC, the University of Utah has been acquiring data on the earliest stage of crack initiation based on the interrupted testing of Waspaloy material specimens. Also, work to identify specific material property features using OIM and SEM equipment has been undertaken. The University of Utah research has served as the basis for VEXTEC conclusions about parameter mapping benefits and future onboard sensed data needs.

Preliminary evaluation suggests that Waspaloy specimen test failures were highly sensitive to:

- Large grains
- High microstress
- Low frictional strength
- Large defects

For example, Figure 4 presents data collected on failure as influenced by grain size. As shown, the larger grains are responsible for most specimen failures.

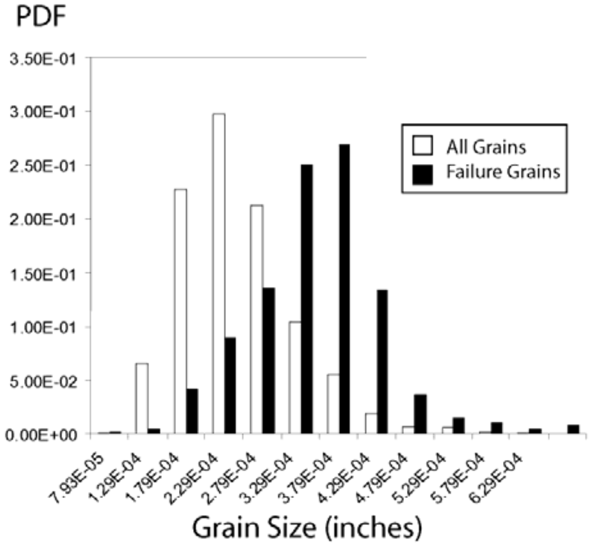


Figure 4. Grain size sensitivity to failure

Using the VEXTEC-developed material modeling approach, 500 specimen (bar) samples were fatigue tested through simulation. Each bar was designed to have a known surface but random interior to simulate parameter mapping (sensed) data. At 90ksi, 441 bars failed but 63% of these failures occurred within 9 individual grains. Similarly at 100ksi, 345 bars failed but 69% of these failures occurred with 6 individual grains. The fact that such a few number of grains account for most failures is significant in consideration of the fact that each bar represents approximately 300,000 individual grains. Certainly this adds creditability to the VEXTEC premise that (sensor) surface mapping could be used as an early-on technique for identifying life-limited components.

6. SUMMARY

Material-based simulation techniques add significant capability to developing prognosis architectural schemes. Particularly with regard to very small crack growth and cases where no advanced fault warning exists, material-based techniques overcome fault to failure modeling limitations.

The VEXTEC developed probabilistic, microstructural modeling approach can be used to predict crack initiation and growth to failure. This methodology has already been proven useful with high strength materials such as turbine engine disks, fans, and blades. Further research conducted by VEXTEC indicates that parameter mapping of the component surface and be used as an effective indicator of life limitations.

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Robert Tryon *is co-founder and Senior Development Engineer at VEXTEC Corporation. He has been involved in the development of reliability software for the automotive industry and for the patent-pending "MICRO" software under Air Force grant funding. He served as principal investigator on VEXTEC's DARPA prognostic technology development projects and has served in a similar role on numerous other projects. He received a Ph.D. in structural engineering from Vanderbilt University and an M.S. and B.S. in mechanical engineering from Rose Hulman Institute of Technology.* .