ICME at GE: Accelerating the Insertion of New Materials and Processes

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The accelerated insertion of materials (AIM) initiative provides the opportunity to reduce the materials development cycle time by up to 50% and thereby lessen the lead time required for new materials and processes. The program was founded to revolutionize the way designers and materials engineers interact, to achieve a leap forward in the application of computational materials science and integration with design engineering tools, and to create an environment where the design/materials team can learn from and build on previous developments. The centerpiece of the AIM system is the designer knowledge base, which provides a framework for managing experimental data, executing linked models describing processing, microstructure, properties, and producibility, and calculating confidence bounds for system predictions.

INTRODUCTION

New materials and processes enable, and often pace, developments in industry. This has certainly been the case for the gas turbine, where a new blade alloy or new melting process can change the face of modern military and commercial aviation. A relentless pursuit continues for "better, faster, cheaper," driven by the market forces that are shaped by customer expectations for improvement. The reality is that materials are now the pacing element in achieving further significant improvements in engine technology. Design engineers are running out of strategies to work around materials limitations, and engine programs are disrupted when new materials are not ready on time. The accelerated insertion of materials (AIM) initiative was conceived, sponsored, and monitored by the U.S. Defense Advanced Research Projects Agency (DARPA) and the U.S. Air Force Research Laboratory (AFRL) to combat this problem.

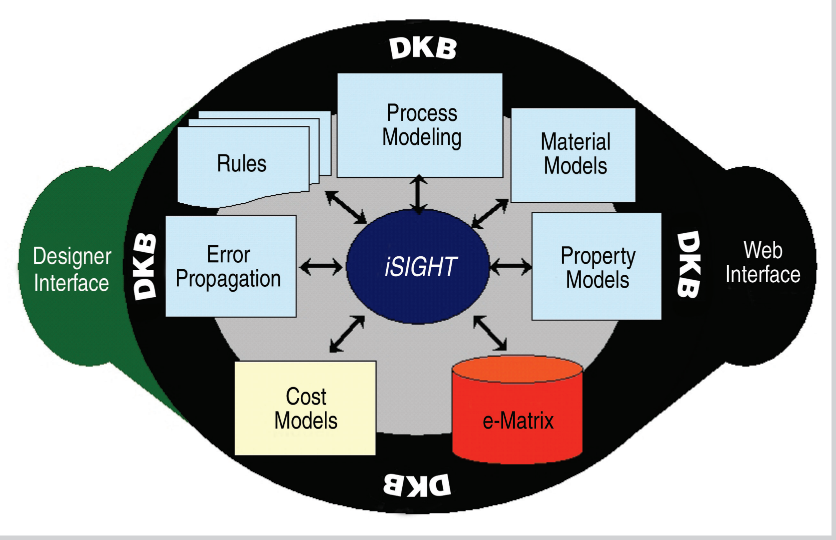

Figure 1. The AIM designer knowledge base system incorporates commercial, proprietary, and emerging computational materials development tools to enable rapid exploration of new materials design space.

The AIM initiative provides the opportunity to reduce the materials development cycle time by up to 50% and thereby lessen the lead time required for new materials and processes. This methodology can be used not only for new alloy introductions, but also for new part or new vendor qualifications, process modifications, or even material non-conformance issues. The AIM program jump-started the concept of integrated computational materials engineering (ICME), being the first to address the growing need in the aviation industry for a coordinated strategy of linking the computational materials tools already available to explore material chemistry and process design space for the optimum alloy composition and thermomechanical processing for a given application.

From 2001–2004, General Electric (GE) Aviation conducted research under the AIM program in collaboration with academia and other partners from industry. While AIM is generically extensible to other materials systems, the GE team used the nickel-based superalloy turbine disk alloy René 88 DT to develop, validate, and demonstrate a system that embodies the AIM methodology.

The program was founded upon bringing about three systemic changes: to revolutionize the way designers and materials engineers interact, to achieve a leap forward in the application of computational materials science and integration with design engineering tools, and to create an environment where the design/materials team can learn from and build on previous developments. The centerpiece of the AIM system is the designer knowledge base (DKB), which provides

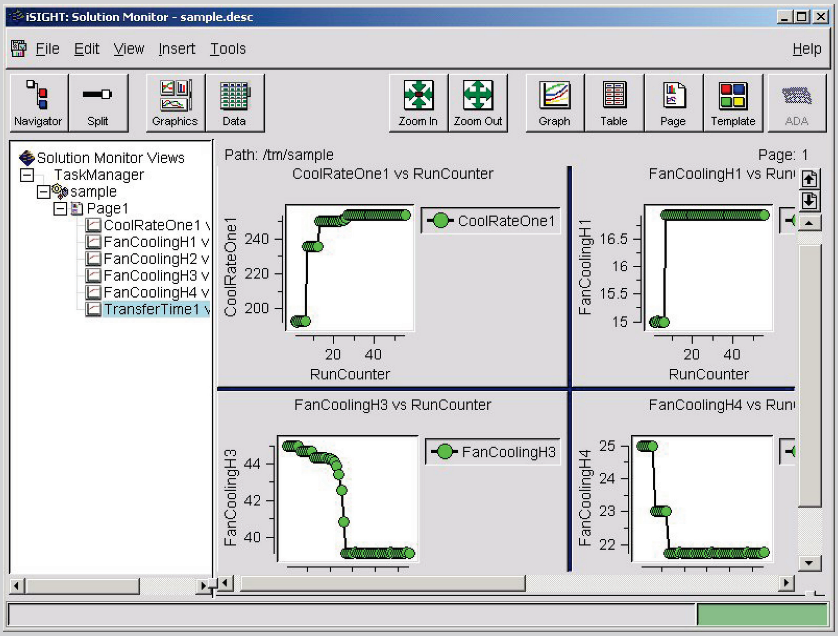

Figure 2. The DKB is dependent on *iSIGHT* to provide integration, optimization, DOE, sensitivity, and uncertainty analysis, with ease-of-use being a prerequisite.

a framework for managing experimental data, executing linked models describing processing, microstructure, properties, and producibility, and calculating confidence bounds for system predictions. The DKB informs design engineers about material performance and producibility as well as transfers materials information to a design engineering trade study tool. The GE team established models, uncertainty methods, and use-cases for integration within the DKB.

Materials Models

Acceleration from the integrated AIM system depends on models with sufficient fidelity and robustness to confidently predict processing, microstructure, and mechanical properties. The GE team employed available and newly developed models to predict the effects of key process parameters on microstructure and properties. Modeling efforts have focused on those that capture the physics governing material-system behavior. Some of the commercially available modeling tools include *Thermo-Calc* (thermodynamics), *DICTRA* (kinetics), and *DEFORM* ® (large-strain deformation and heat-treat thermal modeling).

Uncertainty

The design of a complex system, such as an aircraft engine, must account for uncertainty that is inherent in materials behavior and manufacturing processes. The GE AIM team has evaluated data and modeling uncertainty and applied Monte Carlo analysis to calculate the uncertainty that is produced by variations in processing history, microstructural features, measurement errors, and the inadequacy of physically based models.

Use Cases

The GE team recognized early that models, digitization utilities, and an integration framework are necessary ingredients of an AIM system. However, purpose and benefit are delivered by identifying important problems whose solutions both accelerate development and reduce risk. Use cases, which codify an accelerating methodology and describe the steps toward solving such problems, are the key to success—they provide direction for AIM tool development and ensure that the individual pieces are coordinated to reap a benefit in the end. The GE team established use cases to aid development and testing of the DKB. These use cases included methodologies to design a heat treatment to better balance properties, identify optimum parameters for a dual heat-treatment process, and calculate heat transfer using inverse methods.

In this article, three aspects of the AIM methodology will be explored. First, the AIM DKB architecture will be reviewed and an example of its optimization capability will be demonstrated. Next, the curve generator concept will be discussed, which describes how the DKB can synthesize an average and minimum representation for a given part using a physics-based model along with reduced experimental data input. Finally, the impact of the AIM methodology on the

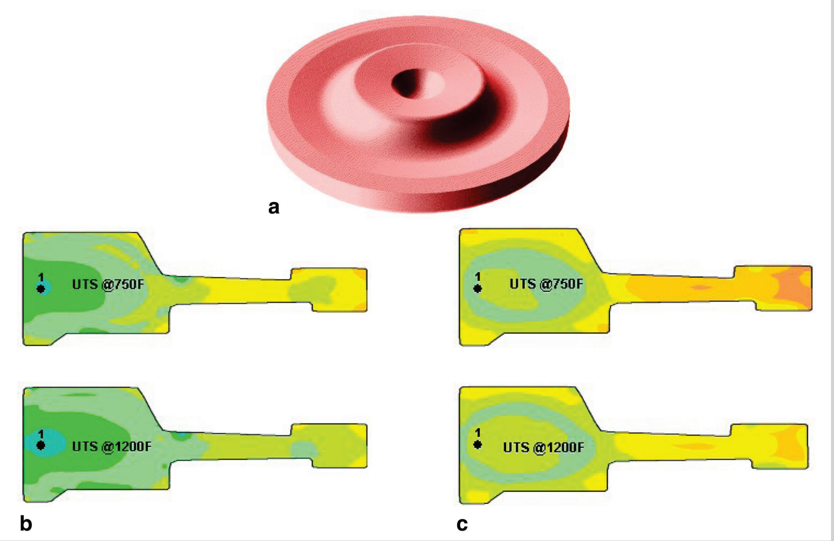

Figure 3. (a) A disk design example where improved ultimate strength was achieved by optimizing the heat-treatment process parameters using the AIM DKB system. (b) Baseline and (c) improved design; only a cross section of a disk is displayed in b and c.

concept of engine prognosis will be reviewed, as it applies to the current DARPA Prognosis program.

THE DESIGNER KNOWLEDGE BASE

During the AIM project, the GE-led team developed a hybrid computational-experimental approach to revolutionize the way in which new materials are developed and flight-qualified for risk-mitigated use in emerging high-performance engines. Key enablers are Engineous Software Inc.'s (ESI) integration and optimization software package (*iSIGHT*™) and an object-oriented database management package from MatrixOne Inc. (*eMATRIX*®). These commercial systems, in conjunction with new computational materials modules and proprietary design software, have been combined to form a flexible, collaborative, computer-based DKB. Major functions include:

- Storage of critical testing data and related processing conditions in a central database such as mechanical and life properties whose fidelity is of primordial importance to engine design
- Integration of the latest physics-based and data-driven models to predict microstructure and material properties and assess complex interaction among processing, structures, and properties
- Automation of the generation of design property curves by combining the usage of historical data, property models, and advanced statistical methods
- Systematic evaluation of propagation of error resulting from processes, material variability, and model accuracy

Given the dynamic, exploratory nature of material research, the DKB system was developed, shown schematically in Figure 1, with the salient features being:

- A custom, dynamic, component-based integration framework utilizing the latest *Java 2 Enterprise Edition* standard to provide a flexible plug-and-play environment that facilitates the integration of new data and models
- *iSIGHT* as the backbone to perform complex integration and execution of a variety of tools and modules ranging from data-driven response surface functions to complex finite-element codes, design of experiments (DOE), multidisciplinary optimization, and uncertainty analysis, which are required throughout the material development process
- An object-oriented database management system based on *eMATRIX* to store complex test, prediction, and design data

Engineering analysis tools have matured over several decades, while computational materials development tools are relatively embryonic.

- Computational materials models for predicting a variety of critical quantities such as microstructure, mechanical properties, process parameters, etc.

DKB Integration Framework

It is well understood that materials processing (e.g., forging and heat treatment) directly impacts the material's microstructure and, ultimately, the resulting mechanical properties. Successful adoption of the AIM philosophy is dependent on the system's ability to effectively translate a set of process parameters for a new material into the targeted mechanical properties, as driven by design requirements. Engineering analysis tools have matured over several decades, while computational materials development tools are relatively embryonic. The ability to integrate and evolve these two worlds is critical to the success of AIM. To ease this migration, the DKB integration framework utilizes a standard template to wrap AIM modules (new and legacy), along with a universal procedure to execute these modules in a distributed environment that substantially reduces the efforts of module integration.

In addition, the integration framework has a dynamic, platform-independent custom AIM-specific graphic user interface (GUI) developed using *Java Swing* application programming interfaces. It facilitates and guides users on module selection and parameter setting for DOE, optimization, and uncertainty analysis. The GUI provides a direct interface to *iSIGHT* and the *eMATRIX*.

DKB/*iSIGHT*

The *iSIGHT* system was selected for AIM because it is ideally suited for large-scale enterprise integration and automation, and because of its extensive capabilities in formulating and solving complex optimization, DOE, and reliability problems. *iSIGHT* also provides a graphical interface for real-time monitoring and control of the analysis during execution, as shown in Figure 2. The DKB system has adopted *iSIGHT* as a backbone engine for automating model execution procedures and for performing sensitivity studies, optimization, and uncertainty analysis.

eMatrix Database System

A critical requirement of the AIM program is to capture and effectively use the existing superalloy material data, knowledge-based rules and methods, and forecasted material data, and to use both existing and predicted data in a seamless fashion with other codes and design tools. The DKB leverages the state-of-the-art database management system *eMATRIX* as the central repository for all test, processing, and design data. *eMATRIX* was originally developed for product data management a decade ago, but has become increasingly popular and extended to include product life-cycle management, supplier chain integration, etc. The database developed for the AIM program captures not only typical tabular data, but also complex mathematical expressions and graphical images such as disk cut-up plans and microstructure images.

Application

The AIM methodology, implemented in the form of the DKB system, is being validated and adopted to solve real-world problems. A typical problem the disk designer faces is how to improve the current design or material system to meet new mission requirements. From a material developer's standpoint, such a requirement can often be achieved by improving relevant material properties at critical locations. In order to meet this objective, one has to relate the mechanical properties back to microstructure and the upstream heat treatment process. Using the DKB that encompasses high-fidelity process modeling tools and property models, one can quickly assess if a desired property improvement can be achieved by optimizing key process parameters (e.g., optimizing the convective heat-transfer coefficients during the disk heat treatment process), and if it can increase ultimate tensile strength and decrease hold time fatigue crack growth at critical locations, as shown in Figure 3. The optimized parameters can then be checked against the process capability of the disk supplier.

AIM: A New Paradigm

As material developers are increasingly challenged by engine designers to develop higher-performance or lower-cost material systems, in a much shorter development cycle time, there has been a critical need to revolutionize the traditional way to conduct new material insertion. The concept and methodology developed by the AIM team has introduced a new paradigm to material developers: shorten the development cycle through the effective use of existing knowledge, advanced modeling tools, and latest computing technologies. The DKB system employs such a concept and has effectively integrated the existing knowledge/data with high-fidelity, physics-based material models and modern computational tools. The benefits of the AIM methodology will become increasingly evident to the materials community in the foreseeable future through use of the DKB system.

THE GENERATION OF MECHANICAL PROPERTY CURVES

The AIM methodology helps the materials engineer by allowing faster and less expensive assessment of material properties. Every day, materials engineers make decisions concerning material selection, the design of new materials, processing modifications, quality control plans, and the qualification of new suppliers. Mechanical properties guide these decisions with a focus on minimum properties, particularly for critical structural materials and their application. Acquiring this information can be both expensive and time consuming because large data sets are needed to accurately quantify behavioral uncertainty. Often, qualifying a metallic material and process requires testing multiple lots of material from different heats involving several suppliers for the full spectrum of relevant properties. Traditionally, this test data is analyzed to produce minimum curves by using classical statistical methods.

The GE AIM program undertook the task to create a curve generator that would allow faster analysis, exercise both data and models, permit earlier assessment of uncertainty compared to traditional methods, and automate the delivery of property curves to both materials and design engineers. The development approach was founded on the following considerations.

Given the current level of confidence in modeling predictions and the requirements imposed by regulatory agencies and design practices, any process for generating minimum mechanical property curves needs to include data for the foreseeable future. The curve generator should employ physically based models where possible. However, data-driven models or transfer functions can be substituted when model execution time is excessive or when no physically based model is available. Traditional statistical curve-generation processes succeed in accurately characterizing minimum behavior only by building diverse databases that cover the full spectrum of variance sources. Since accurate determination of variance is the driver for cost and duration, the AIM curve generator needs to invoke methods to streamline the estimation of property variance.

Given these precepts, the GE team built a curve-generator module and integrated it into the DKB. As suggested previously, the approach was to blend conventional statistical mechanical property analysis with complementary model-based methods. The overall strategy is shown in simplified form in the block diagram of Figure 4.

Physically based models representing process, microstructure, and the subject mechanical property are used to determine the shape of the property curve (e.g., the functional dependence of yield strength with temperature). However, available property data is used to calibrate the model thereby determining the curve's location. Once the average curve is established, the data residuals (data offsets from the average curve) are analyzed using standard analysis of variance techniques. When the amount of data is limited, this variance estimate is uncertain; therefore, a second variance estimate is calculated using Monte Carlo techniques.

The Monte Carlo method involves characterizing the variation of process parameters among production lots, the distribution of processing conditions within a part, and the error associated with the test method. These characterized sources of variation are then used to perturb linked models describing processing, microstructural evolution, and property development. Repeating this process a large number of times provides a probability density function and variance for the predicted mechanical property.

This curve-generation process was implemented in an *Excel* workbook, which lays out the analysis via a logical workflow that steps the analyst through the sequence of analysis operations. The workbook exploits *Excel* as a well-known user interface but also stores the input data, plots property curve predictions, and employs visual basic for applications scripts and *Excel* functions to execute models and perform statistical calculations.

The AIM curve generator was applied to analyze the tensile yield strength for a high-performance superalloy used for turbine disk applications. Models used during analysis included *DEFORM* to characterize quench rate throughout a disk forging, a physically based precipitation model developed by GE to determine the influence of thermal history upon the size distribution of the gamma-prime precipitates, and a yield-strength model developed by the University of Michigan. The first two of these models were incorporated within the curve generator as transfer functions derived from numerous modeling runs.

One of the worksheets within the curve

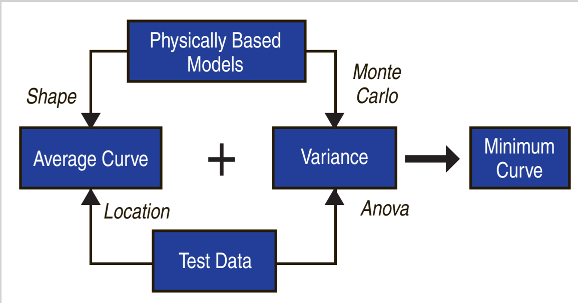

Figure 4. The process used by the AIM curve generator.

generator is shown in Figure 5. For this example, 66 data points were used to calculate minimum yield strength. The AIM curve generator prediction of minimum at the 50% and 90% confidence levels bracket the historical design minimum despite the fact that the latter curve was derived from over 500 data points. This shows the potential for significant reduction in the quantity of data required by the AIM curve-generator process.

The AIM curve generator, once fully developed, offers a number of significant benefits. First, by enabling automated estimation of minimum mechanical property capability with less data, the AIM process contributes to accelerated insertion by allowing earlier and more frequent assessments of material capability. This acceleration allows the designer to confirm the adequacy of material and process enhancements and thereby reduces insertion risk. Also, through automation of the process, this module can be linked with the design system via the DKB, further enhancing the designer's ability and opportunity to conduct "what-if" sensitivity analyses and produce superior designs.

APPLICATION OF AIM TO ENGINE PROGNOSIS

The vision of prognosis (or prognostics) is the real-time management of fleet assets. In an engine sense this means avoiding mishaps through safety improvements, saving costs through achieving full-life entitlement of life-limited parts, and increasing readiness through increased time on wing. Prognosis entails making a future prediction based on expected usage as well as accurately defining the current state of an asset or subcomponent. To do this, accurate mechanistic models are required that can predict outside of the current state knowledge. The key to all of this is in reducing uncertainty about the remaining life. Current methods predict the life of parts based upon fleet-wide statistics with a hard life limit. Once the hard limit has been met, all parts are retired. Figure 6 shows that parts will be retired with significant remaining life. It has been determined that the two greatest sources of uncertainty are the use environment and material property variation. The use environment piece translates to accurately knowing the temperatures and stresses on an individual engine/part basis. To achieve this information, work is progressing on improved real-time temperature measurements and a parts life tracking system that will download every mission point from every engine in the fleet and predict life based on actual usage. The materials property uncertainty is best addressed using AIM-type material models. Examples of these models include grain-size predictive process-property models for rotating parts such as turbine disks. This effect is shown in Figure 7a for typical nickel-based superalloys at constant alternating stress levels and temperature. Typically, processing conditions will result in finer grains toward the rim and coarser grains toward the bore. This can result in significant material property variation throughout a component. Another example would be the alignment and dendrite arm spacing in single-crystal airfoil materials. Figure 7b shows this effect for a typical single-crystal nickel-based superalloy at constant alternating stress levels and temperature.

AIM IMPLEMENTATION STATUS AND FUTURE WORK

GE Aviation is committed to using AIM across its Materials and Process Engineering Department (MPED) and throughout its engineering division. Despite the lack of full maturity for some models within the AIM DKB, a core group of engineers has learned to use the system, identified further use cases, and begun to implement some of the modules within the technology program and the design process. Accelerated

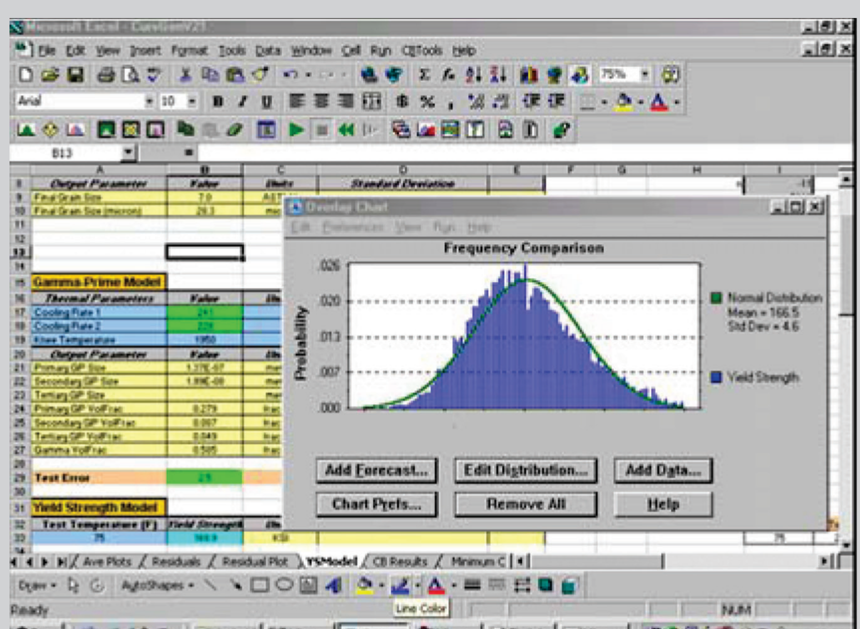

Figure 5. The results obtained from the AIM curve generator for a turbine disk alloy.

insertion of materials complements both GE's corporate commitment to Six Sigma methods and extensive efforts to digitize engineering processes. In addition, DKB software was transitioned to a major forging supplier and AIM program team member, Ladish Company, Inc., of Cudahy, Wisconsin. There, it was used by the company's engineers during validation exercises to predict the microstructure and mechanical properties following training by the GE Global Research Center's AIM developers. Future implementation of the DKB system will focus on using the ESI Federated Intelligent Product Environment system, the successor to *iSIGHT*, for its ease of new model integration, back compatibility with *iSIGHT* modules, and business-to-business web capabilities. The AIM curve generator was demonstrated within MPED's Material Behavior Section, which is adapting the module approach to streamline and automate present methods to produce design minimum curves.

The Trade Study Tool (TST) has been reviewed with the GE Aviation Engineering Department leadership, design practice owners, and the department's chief engineer. It has been approved for regular use by designers and is the preferred tool for conducting disk burst analyses. The TST has also been applied in a NASA-funded contract to carry out a trade study for an advanced, dual-heat-treated disk. In a separate AFRL-funded effort, GE has adapted the AIM precipitation and creep models to the René 104 advanced disk alloy to support design analysis of an elevated-temperature spin pit test.

Overall, programs adopting the AIM approach include DARPA's Prognosis program, follow-on AFRL AIM programs, and the Air Force Office of Scientific Research Materials Engineering for Affordable New Systems program. Internally, GE is pursuing the application of AIM methodology to new niobium silicide materials, airfoil superalloys and coatings systems, titanium alloys, and composite systems.

While further work is required to realize the full potential of the AIM system and its methodologies, the GE team has demonstrated a process for integrating materials, design, and supplier efforts. The team has created a first-generation AIM process and DKB that incorporates the models, integration utilities, and analysis tools necessary to carry out meaningful analyses. Using these capabilities, the engine development team can produce design data curves and material-design trade studies earlier than possible with conventional data-driven methods. Also, the team can apply the DKB to execute use cases that optimize processing and properties, and improve design applications of both new and existing materials.

GE Aviation has begun to implement AIM methodologies and is committed to exploiting modeling across materials and engine components. These methodologies have paved the way for a major upswing of materials analysis and digitization that can only lead to greater exploitation of materials technology throughout the product with greater savings of cost and time. Once the AIM revolution is complete, the designer will be able to deploy materials with greater confidence knowing that both data and theory jointly combine to validate the developments. This first example of "integrated computational materials engineering" will allow a new generation of materials, mechanical, and manufacturing engineers to use less time and resources to continue to push the limits of gas turbine technology.

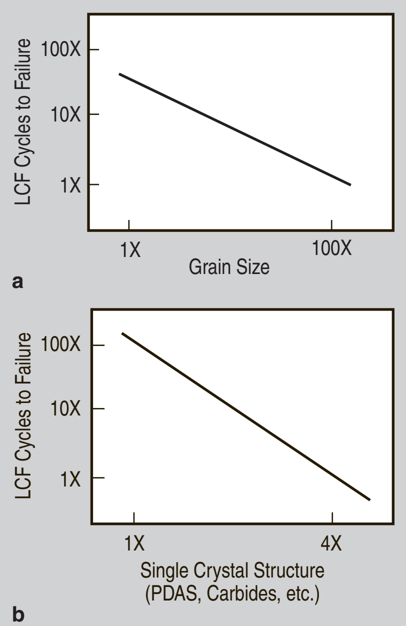

Figure 7. (a) The grain size effect on low-cycle fatigue (LCF) life and (b) the effect of single-crystal dendrite arm spacing on LCF life.

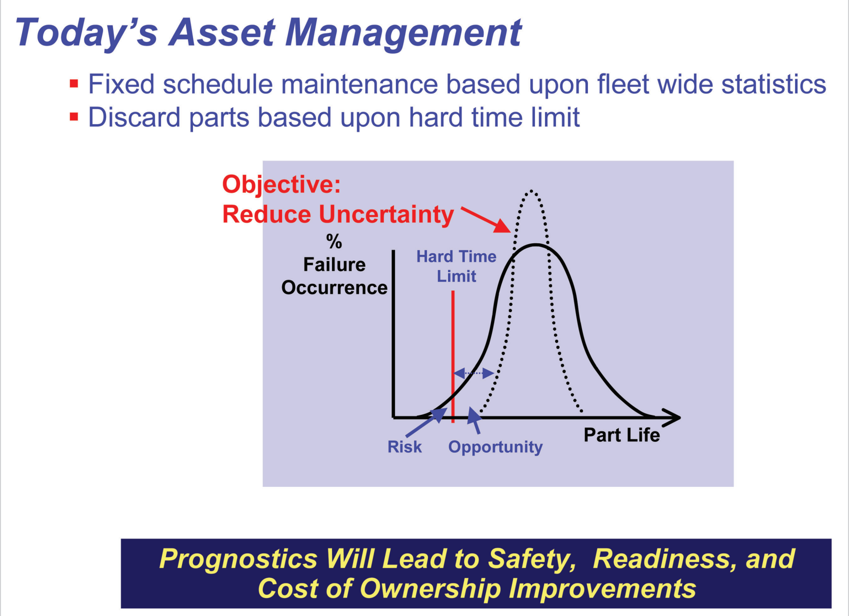

Figure 6. Current asset management practice.

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