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UNDERSTANDING MATERIALS UNCERTAINTY FOR PROGNOSIS OF ADVANCED TURBINE ENGINE MATERIALS (PREPRINT)

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14. ABSTRACT

Materials damage prognosis offers the opportunity to revolutionize life management of advanced materials and structures through a combination of improved state awareness, physically based predictive models of damage and failure, and autonomic reasoning. Historically, lifetime and reliability limits for advanced fracture-critical turbine engine materials have been based on expected worst-case total life under fatigue. Recent findings in a variety of advanced propulsion alloys indicate that the life-limiting mechanisms are typically dominated by the growth of damage that begins at the scale of key microstructural features. Such behavior provides new avenues for management and reduction of uncertainty in prognosis capability under conditions that depend on damage tolerance. To examine a range of sources of uncertainty in behavior and models of such behavior, this paper explores the following topics: (a) Duality in Fatigue, (b) Relaxation of Surface Residual Stresses in Laboratory Specimens, (c) Relaxation of Bulk Residual Stresses in Components, (d) Nonlinear Acoustic Parameter for the Detection of Precursor Fatigue Damage, (e) Elevated Temperature Fretting Fatigue, (f) Crack Growth under Spin Pit Environments, and (g) Crack Growth Under Variable Amplitude High Cycle Fatigue (HCF) Loading. Based on the findings, we outline avenues for further technology development, maturation, validation, and transition of mechanistically based models that have the potential to reduce predictive uncertainty for current and future materials.

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Understanding Materials Uncertainty for Prognosis of Advanced Turbine Engine Materials

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Materials damage prognosis offers the opportunity to revolutionize life management of advanced materials and structures through a combination of improved state awareness, physically based predictive models of damage and failure, and autonomic reasoning. Historically, lifetime and reliability limits for advanced fracture-critical turbine engine materials have been based on expected worst-case total life under fatigue. Recent findings in a variety of advanced propulsion alloys indicate that the life-limiting mechanisms are typically dominated by the growth of damage that begins at the scale of key microstructural features. Such behavior provides new avenues for management and reduction of uncertainty in prognosis capability under conditions that depend on damage tolerance. To examine a range of sources of uncertainty in behavior and models of such behavior, this paper explores the following topics: (a) Duality in Fatigue, (b) Relaxation of Surface Residual Stresses in Laboratory Specimens, (c) Relaxation of Bulk Residual Stresses in Components, (d) Nonlinear Acoustic Parameter for the Detection of Precursor Fatigue Damage, (e) Elevated Temperature Fretting Fatigue, (f) Crack Growth under Spin Pit Environments, and (g) Crack Growth Under Variable Amplitude High Cycle Fatigue (HCF) Loading. Based on the findings, we outline avenues for further technology development, maturation, validation, and transition of mechanistically based models that have the potential to reduce predictive uncertainty for current and future materials.

Nomenclature

$f_t(N)$ = probability density of the total lifetime
$f_l(N)$ = probability density of the crack growth lifetime
$f_m(N)$ = probability density of the total lifetime
p_l = probability of occurrence of the life limiting mode of failure
p_m = probability of occurrence of the mean life mode of failure

I. Introduction

Based on decades of experimentation, analysis, and field experience on aircraft turbine engines, the Air Force has developed a service-life management specification defined by the Engine Structural Integrity Program (ENSIP).[1] To assure safety and reliability, this specification requires that design and operation of fracture critical turbine-engine components, such as disks and spacers, satisfy both safe-life and damage tolerance approaches. Much of the experience that underlies ENSIP has been largely empirical, however, and the allowable service lifetimes have been based on traditional views of statistical behavior of materials. Currently, such lifetime and reliability limits for advanced fracture-critical turbine engine materials are based on the expected worst-case total lifetime under fatigue. On a component-by-component basis, this approach may be overly conservative, however, and more accurate and realistic life methods are needed to combat the growing cost of engine sustainment, while continuing to maintain high safety and reliability.

Under a program known as *Prognosis*, spearheaded by Dr Leo Christodoulou, the Defense Advanced Research Projects Agency (DARPA), the Air Force, and the Navy have been pursuing a transformational new vision for high fidelity life management of advanced aerospace systems and subsystems.[2,3] The approach of the *Prognosis* program is to develop and integrate new capabilities for (i) real-time damage state awareness, (ii) physics-based damage and failure modeling, and (iii) autonomic reasoning to provide revolutionary improvement in reliability and life management methods for advanced materials and structures. In 2003, DARPA awarded contracts for the Structural

Integrity Prognosis System (SIPS) and the Engine System Prognosis (ESP) programs, which were targeted principally to Navy aircraft and Air Force turbine engines, respectively, to demonstrate the feasibility and value of the Prognosis approach in real-world applications. The SIPS program was led by Northrop-Grumman Corporation in collaboration with the Navy, while the ESP program was led by the team of GE Aviation and Pratt & Whitney, in collaboration with the Air Force. Although these demonstration programs were performed on legacy aircraft and engines, the principles of the Prognosis technology are quite generic and have broad application to emerging and future flight systems in both the military and commercial sectors.

II. Sources of Uncertainty in Life Management

As part of the ESP program, the current authors were members of the Air Force team tasked with developing fundamental understanding of the factors that control variability and uncertainty in life prediction. This involved mechanistic based model development and a range of research and development tasks that were directly integrated with the industry contract programs. Highlights of these tasks are presented below.

A. Duality in Fatigue

A physically-based approach for describing fatigue variability of turbine engine materials was developed and implemented in a probabilistic life prediction method[4-6]. This new understanding of fatigue variability may potentially reduce the uncertainty in life prediction over the current lifing practices. The method can also have an equally important influence on design of materials for fatigue properties.

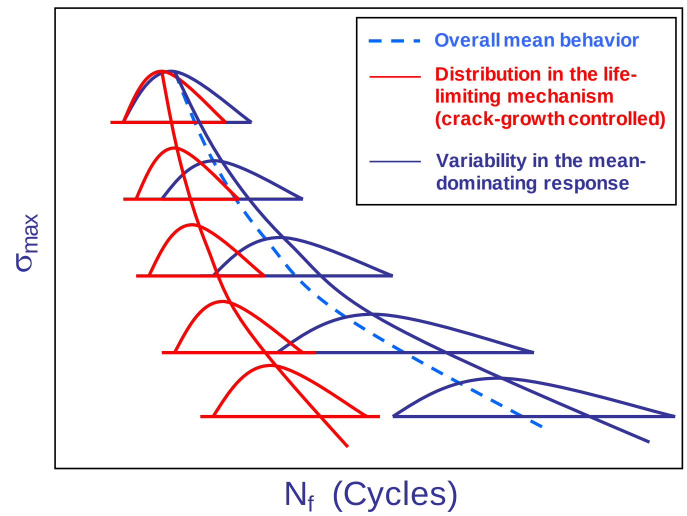


Figure 1: Schematic illustration of the duality in fatigue behavior

Primary tenets of the new fatigue variability description can be summarized into the following points.[7,8] (i) Under any nominal microstructural and loading condition, a hierarchy of local deformation heterogeneities develop in the sample which relate to certain randomly occurring microstructural arrangements or features; (ii) Due to this hierarchy, probability exists of an extreme microstructural arrangement which may initiate a predominantly crack-growth dominated failure, producing a life-limiting failure distribution; (iii) Different rates of influence of a given variable on crack growth and the mean-lifetime (which can have a negligible to an overwhelming contribution from the crack-initiation regime) promotes disparate trends in the minimum and the mean behavior (or dual fatigue response) with respect to the variable. Figure 1 provides a schematic illustration of the dual-fatigue behavior.[9] The effect of stress level on mean versus the life-limiting fatigue responses is depicted in the figure, but the same understanding can be extended to other variables such as microstructure, surface treatment, temperature, and dwell time. The implications are, first, that any variable directed at affecting the mean-fatigue behavior influences the minimum behavior to a different degree. Second, an understanding of the mean-fatigue relationship to the variable does not capture how the limiting lifetime might respond.

The above understanding when applied to fatigue design of materials suggests that any compositional, processing, or microstructural modification needs to be focused at the lower-lifetime limit and the associated controlling microstructural configurations, which may not be accurately determined by purely statistical or mean-fatigue based approaches. The proposed method, however, enables such a material development process by providing a mechanistic basis for the limiting fatigue behavior.

The new description of fatigue variability as it applies to a few specific cases is presented in Fig. 2. The effect of stress level on the fatigue variability behavior of Ti-6Al-2Sn-4Zr-6Mo (Ti-6-2-4-6)[5, 6] is shown in Fig. 2(a). As depicted in the figure, the mean lifetime follows a rapidly increasing trend with a decrease in the stress level, which is attributed to the increasing contribution from the crack initiation regime. On the other hand, the limiting behavior remains almost unchanged within the range of stresses considered. Furthermore, as indicated by the hatched region,

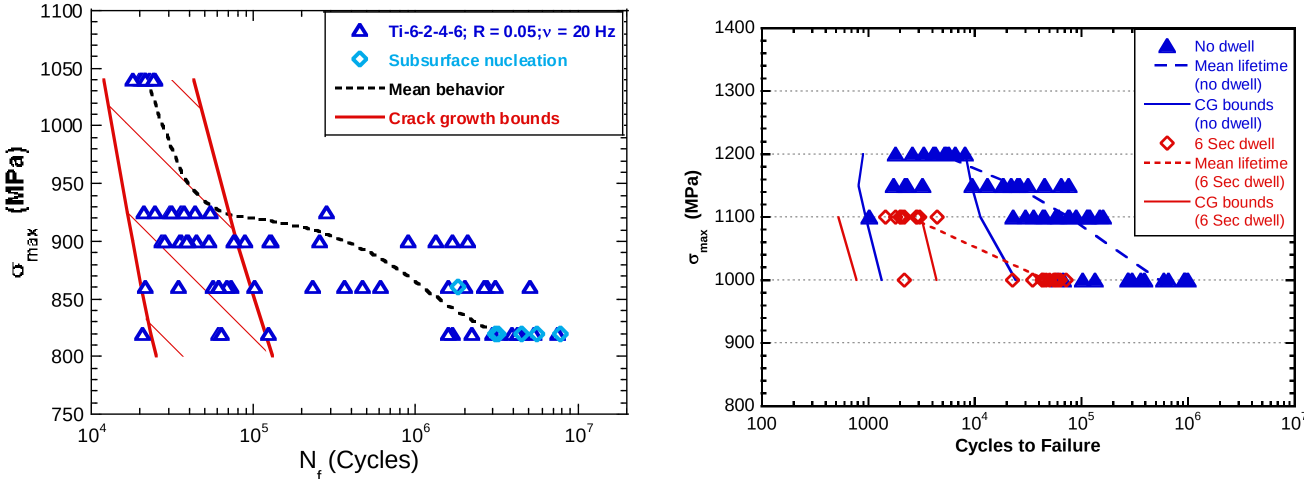


Figure 2: Separation of mean from the crack-growth-controlled response in (a) Ti-6-2-4-6 and (b) IN100

the crack growth lifetime bounds describe the life-limiting points and the trend thereof with respect to stress level. The control of crack growth on the limiting behavior produces an increasing separation of the mean lifetime with decreasing stress thereby increasing the variability in total lifetime.

Figure 2(b) is an illustration of the application of this approach in understanding the influence of dwell-time on fatigue variability in IN100, a Ni-base superalloy. For a given dwell time, IN100 displays a similar behavior as Ti-6-2-4-6. The effect of dwell time on fatigue variability can be rationalized by separately accounting for its influence on the mean lifetime and the crack-growth lifetime. Therefore, although a dwell time of 6 seconds decreases the mean lifetime, it affects the minimum lifetime to a smaller degree, producing a decrease in lifetime variability.

It is important to note, that by crack growth lifetime we imply both the small and the long crack regimes. An important outcome of this study was the understanding that the small and the long crack regimes are impacted to widely varying degrees by dwell time. This is depicted in Fig. 3 where the influence of 6 second dwell at peak load on the long versus the small crack regime in IN100 is presented[7,8]. While the dwell period had negligible effect on the long crack growth rates, the small crack growth rates were dramatically increased when tested at the same stress level and need to be accounted for in life prediction. Further, an accurate calculation of lifetime variability also necessitates incorporating the increased variability in growth rates in the small-crack regime into the life prediction method, as described in a later section.

Application of the physics-based description to fatigue variability under surface residual stress

Surface treatments such as shot-peening are imparted to promote slower crack initiation and propagation in the surface and thereby increase the lifetime. The hypothesis developed in this study suggests that the effect of shot-peening on the lifetime distribution should be represented in terms of its effect on the mean and the limiting behavior. This point is illustrated by the example presented in Fig. 4 where the influence of shot-peening on fatigue variability in two microstructures of Ti-6-2-4-6 at 260 °C is presented. As evident in the figure, shot-peening increased the mean lifetime in both cases by mitigating crack-initiation on the primary α scale (on the order of 10

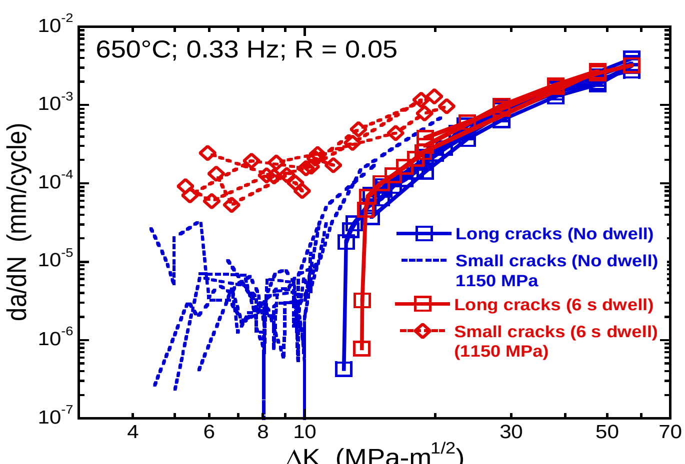


Figure 3: Effect of dwell time on the long vs. the small-crack growth regime in IN100

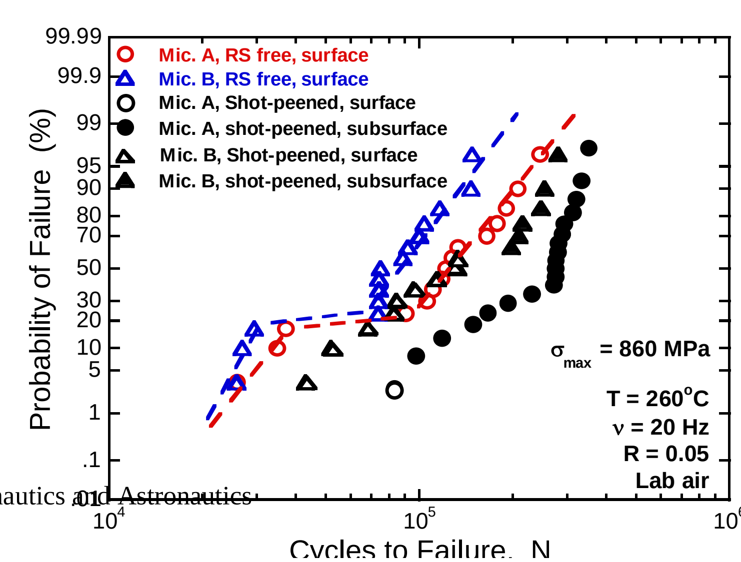


Figure 4: Effect of shot-peening on the mean vs. life-limiting fatigue response in two microstructures of Ti-6-2-4-6 at 260 °C.

μm) in the surface which would have otherwise occurred in a residual-stress free condition, and forcing crack-initiation to the subsurface in many samples. This can be attributed to the effect of nominal residual stress profile. Although the subsurface mechanism improved the mean response, the life-limiting failures under shot-peening occurred by a different surface crack-initiation mechanism in which crack was found to originate from shot-peening – local-microstructure interaction sites where the crack initiation sizes appeared to be significantly larger (on the order of 100 μm) than the primary α size scale seen in the residual stress free case. The limiting lifetimes under shot-peening, therefore, approached those under the residual-stress free condition, especially in microstructure B.

Probabilistic Life-Prediction Modeling

The physics-based understanding of fatigue variability was implemented in a probabilistic life-prediction model.[6, 7] In this, the lifetime distribution was modeled as superposition of the crack growth lifetime and the mean lifetime probability densities. The total lifetime density can, therefore, be represented by:

$$f_t(N) = p_l f_l(N) + p_m f_m(N)$$

Where, $f_t(N)$, $f_l(N)$, and $f_m(N)$ are probability densities representing the total lifetime, crack growth lifetime, and the mean lifetime respectively. The factors, p_l and p_m are the probability of occurrences of the respective responses. Salient proposals of the model are, first, that the effect of any variable on lifetime distribution is separated into its influence on crack growth and the mean lifetime behaviors. Second, the lifetime distribution is modeled as a superposition of these two responses.

Examples of application of the model in predicting the lifetime distribution as a function of key variables are presented in Fig. 5. Prediction of the effect of temperature on lifetime variability in Ti-6-2-4-6 is shown in Fig. 5(a) [3]. As evident in the figure, an increase in temperature from 23 to 260 °C, while keeping the stress level constant, resulted in a significant decrease in the mean-dominating behavior but the minimum lifetime remained invariant. However, going from 260 to 399 °C, while the mean-dominating behavior remained almost unchanged, the minimum response decreased. The model proved to be well-suited to capture these relative changes in the separation between the mean and the life-limiting responses, as illustrated by the figure.

Figure 5(b) shows predictions of the effect of stress level under a dwell time of 6 seconds on lifetime distribution in IN100. Again, the model accurately captures the disparate trends in the mean and the life-limiting behavior in dwell fatigue with respect to stress level. In particular, the prediction of minimum behavior in this model is not data-driven but mechanistically based. As such, a more accurate representation of the life-limiting behavior is provided without heavy dependence on data, thereby reducing the uncertainty in the lifetime limits.

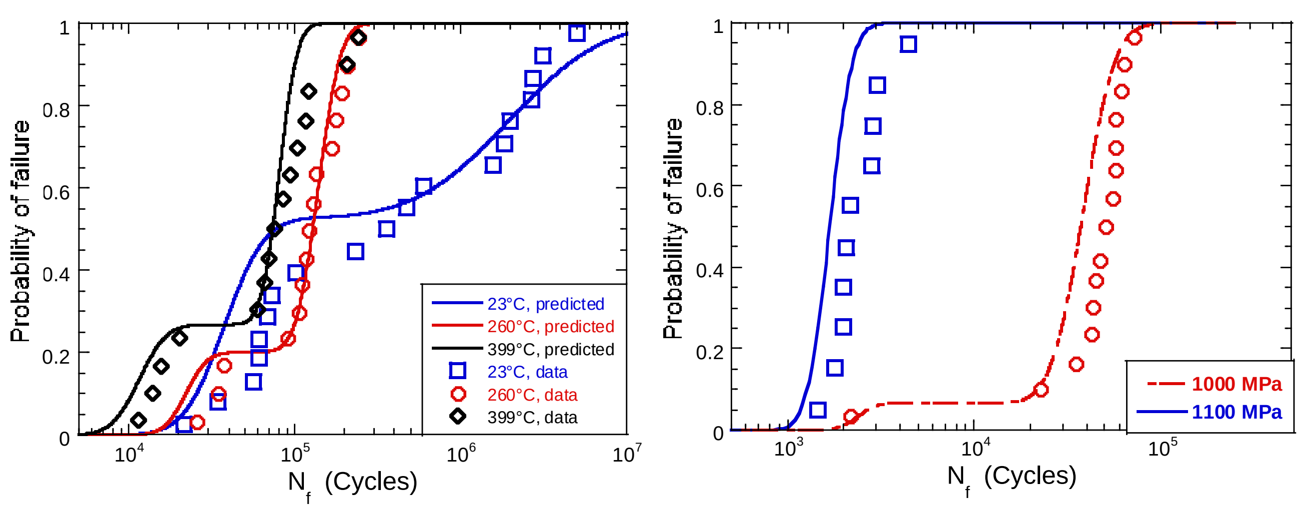


Figure 5: Probabilistic model predictions of (a) the effect of temperature on fatigue variability in Ti-6-2-4-6 and (b) the influence of dwell time on lifetime distribution in IN100

From a design-life perspective (for example, B0.1 lifetime limit), it can be shown that the prediction of lifetime limit by the crack-growth lifetime density, $f_l(N)$ (i.e., in the limit of $p_l \rightarrow 1$) forms a lower bound of predictions by the bimodal model. Examples of prediction of probabilistic lifetime limit in Ti-6-2-4-6 and IN100 are shown in Fig. 6 (a) and (b), respectively. As depicted in Fig. 6(a), the simulated crack growth lifetime density, $f_l(N)$, agrees reasonably well with the distribution in the life-limiting points. The B0.1 lifetime predicted by this method is significantly higher in this case than that by an empirical data-based approach, since the latter method does not recognize the superposition of dual responses. On the other end of the spectrum, depending on the amount of data and the probability of occurrence of the life-limiting mechanism, the empirical method may not always capture the limiting behavior resulting in an over-prediction of the lifetime limit. This is illustrated by the condition presented in Fig. 6(b). The figure depicts the prediction of B0.1 lifetime by the function, $f_l(N)$ and by the empirical method in dwell fatigue of IN100. Due to the rarity of the life-limiting mechanism, the empirically derived B0.1 lifetime is an over-prediction in this case. As shown, the proposed approach captures the limiting failure and provides a more accurate prediction of B0.1 lifetime, therefore, minimizing the uncertainty in prediction of the same.

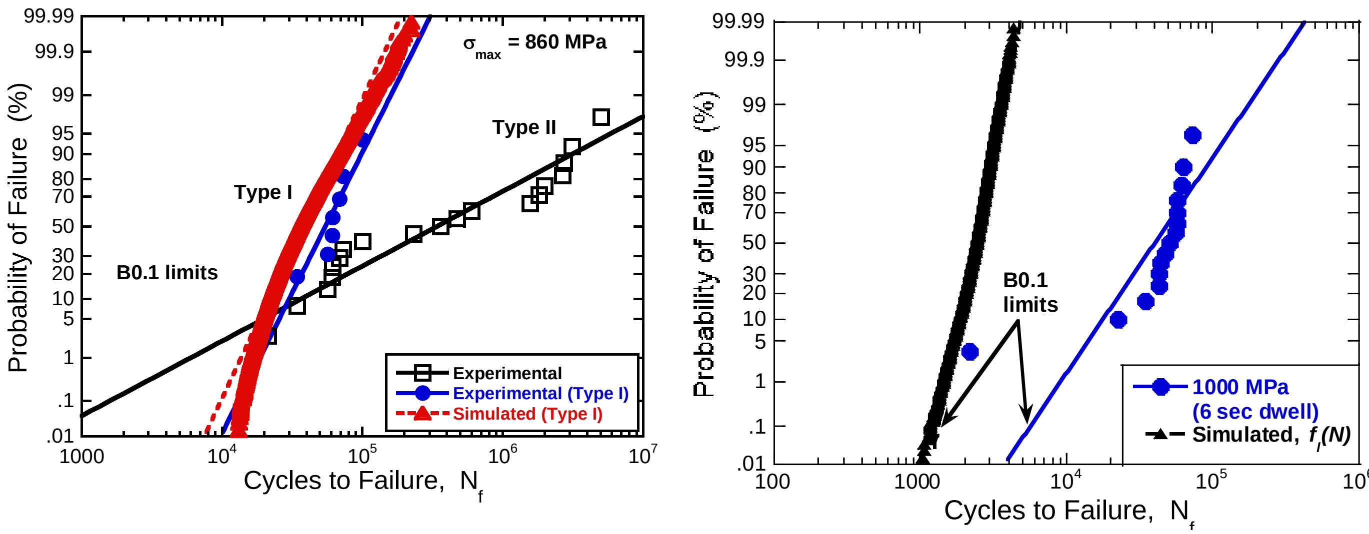


Figure 6: Comparison between predictions of life-limiting behavior and B0.1 lifetime by the proposed probabilistic model and the empirical approach in (a) Ti-6-2-4-6 and (b) IN100

B. Relaxation of Surface Residual Stresses in Laboratory Specimens

Relaxation of shot peened residual stresses in advanced turbine engine alloys (Ti-6Al-2Sn-4Zr-6Mo, IN100) were investigated for a number of service loading conditions including elevated temperature thermal exposure, a single load-unload cycle, fatigue loading, and sustained (creep) loading.[10-13] Brief highlights of these studies are summarized below.

A coupled creep-plasticity model was developed to predict relaxation of shot peened (SP) residual stresses in IN100. The model incorporates the dominant creep deformation mechanism, coupling between the creep and plasticity models, and effects of prior plastic strain. Model predictions correlate well with experimental results on shot-peened dogbone specimens subject to single cycle at elevated temperature as shown in Figure 4a. The predictions accurately capture both the shape and magnitude of the retained residual stress profile.

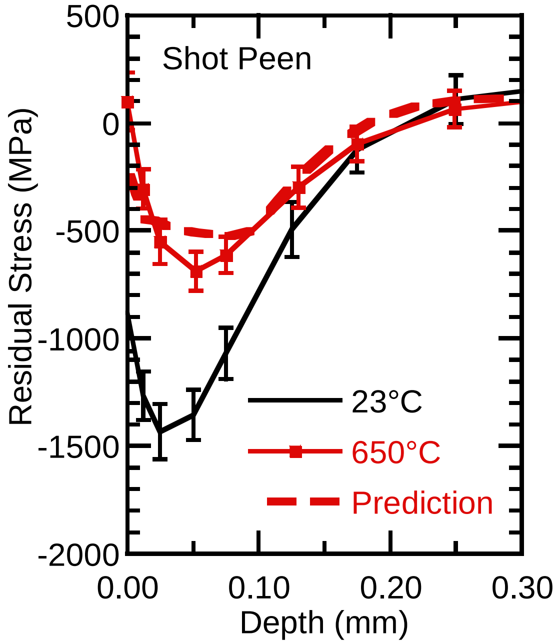


Figure 7a Prediction for retained residual stresses in shot peened dogbone specimen from single load-unload cycle in IN100 at 900MPa and 650°C.

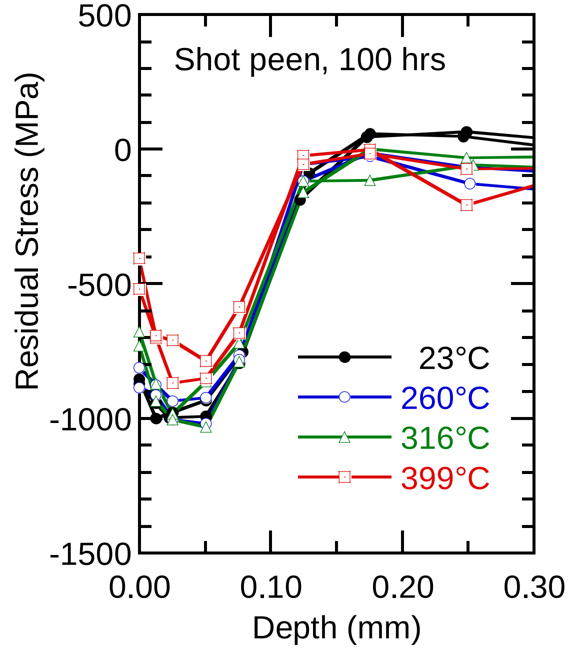


Figure 7b Effect of thermal exposure of up to 100 hours on the shot peen residual stress in Ti-6Al-2Sn-4Zr-6Mo for temperatures 23 to 399°C.

The Ti-6246 cylindrical dogbone specimens used in this study were shot peened to an Almen intensity of 6A and subjected to either isothermal exposure or mechanical cycling at elevated temperatures. Residual stress depth profile measurements made on these specimens are shown in Figure 4b. In the absence of mechanical loads, approximately 80% of the subsurface peak residual stresses are retained, even after 100 hours of exposure to 399°C ≈ 0.35Th (Th = homologous temperature).

The results from interrupted and failed fatigue tests at a maximum stress of σ = 860 MPa are shown in Figure 3. The average relative reduction in subsurface residual stress, compared to the baseline, is approximately 13%, 32%, and 49%, at 260, 316, and 399°C, respectively. These relative changes are significantly higher compared to the relaxation due to thermal exposure shown in Figure 2. Hence the difference between the residual stress relaxation observed under thermal exposure (Fig. 2) and fatigue loading (Fig. 3) can be attributed to the mechanical loading. These applied loading conditions are beyond the expected service operating conditions and yet a significant portion (> 50%) of the beneficial compressive subsurface residual stress is retained.

The retained residual stress profiles in these two turbine engine alloys have been used to study the effects of compressive residual stresses on crack growth retardation under service operating conditions. In general, the crack growth analyses show that it is feasible to significantly extend the crack growth life of components based on partially (25-50%) retained compressive residual stresses [4].

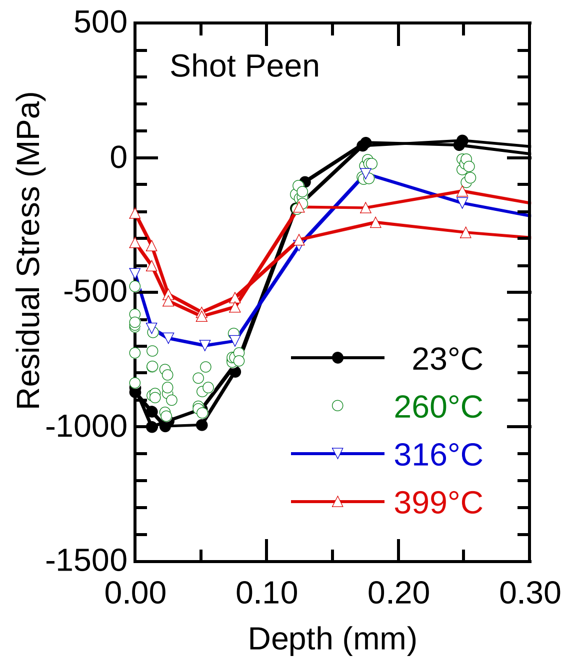


Figure 8 Effect of cyclic loading (860 MPa) on shot peen residual stress in Ti-6Al-2Sn-4Zr-6Mo for temperatures 23 to 399°C.

C. Relaxation of Bulk Residual Stresses in Components

In many cases, the magnitude of bulk residual stresses in turbine disks can be a large fraction of the material's yield strength [14]. The magnitude and distribution of bulk residual stresses in turbine engine rotors and forgings were determined using a hybrid experimental-analytical splitting technique. It was found that the bulk residual stress profiles in different disk geometries can exhibit profiles with opposite signs. For example, the circumferential bulk residual stress at the bore is compressive in one disk geometry, but tensile in another disk geometry. In one particular instance, the predicted bulk residual stress profile from disk splitting was independently verified by processing predictions made by the original equipment manufacturer. These findings have focused awareness on the magnitudes and distributions of bulk residual stress profiles and the importance of developing tools to model and manage their impact on lifing of turbine engine rotors.

D. Nonlinear Acoustic Parameter for the Detection of Precursor Fatigue Damage

A number of material characteristics contribute to nonlinearity of the acoustic behavior of materials called the β parameter. Simply, the β parameter is proportional to the ratio of the second harmonic amplitude to the fundamental amplitude squared, $\beta \propto A_2/A_1^2$, where A_1 is the amplitude of the input frequency, and A_2 is the amplitude of the wave with a frequency twice the input frequency. The material characteristics that can be captured by β are numerous,[e.g. 15,16] but the goal of the current effort[17,18] was to determine if precursor damage could be measured in Waspaloy and IN100 materials. β measurement specimens were extracted from mechanical test coupons or retired turbine engine hardware. These samples were carefully polished and lapped to ensure that machining damage was removed and that the samples were flat and parallel. More details of the experimental technique can be found in17. Fatigue tests were conducted on Waspaloy at 649°C to 25%, 50%, and 75% of life and β was measured. This work found only a limited sensitivity of β to fatigue damage, spatial location, or crack locations even with careful experimental techniques. To assess the use of nonlinear acoustics to measure the precursor fatigue damage in more realistic condition, IN100 specimens were extracted at several locations from two engine disks having distinctly different levels of consumed life. As a control, specimens were also excised from a virgin IN100 forging. The nonlinear acoustic parameter did not show sensitivity to the IN100 component usage history, but β was found to be sensitive to material processing, surface oxidation, shot-peen residual stress, and high temperature exposure. Due to the strong influence of surface condition on β, this parameter did not appear to be a practical, reliable means to measure precursor fatigue damage in the real world.

E. Elevated Temperature Fretting Fatigue

Fretting fatigue occurs when two components are forced together in contact with a small oscillating relative displacement[19]. Fretting can be a significant concern in turbine engine blade to disk attachments, as the local wear and high stresses near the edge of contact can result in nucleation and growth of cracks and a reduction in the life of the component. In this context, fretting fatigue is also referred to as attachment fatigue or edge-of-contact fatigue. The objective of this task was to investigate fretting in a dovetail type attachment similar to that found in a turbine engine blade to disk attachment. The primary focus was on behavior at elevated temperatures typically found near the rim of a first stage turbine disk. The approach was to develop a new fretting fatigue test fixture capable of simulating relevant temperature and loading conditions.

A unique elevated temperature fretting fatigue fixture was developed under this program for testing of dovetail shaped specimens at elevated temperature and is described further in Golden[20]. A drawing of this test setup is shown in Fig. 6, with the 45° flank angle dovetail specimen cyclically loaded into contact with two fretting pads by an MTS hydraulic actuator. The fixture was designed using load cells to measure the contact forces, and furnace igniters placed front and back to heat to the desired temperature. The materials tested were Rene'88DT disk forging nickel-base superalloy for the specimen and Rene'N5 single crystal nickel-base superalloy blade material for the pads. The fixture was designed to accommodate a dovetail specimen, so that both the shear and normal contact forces were cyclic, as would be found in an engine. This complements more conventional fretting fatigue test setups that apply a constant normal force with a cyclic shear force[21]. Fig. 7 is a summary of the test results showing life for several values of maximum remotely applied force, F_{max}, with load ratio, $R = 0.1$. Although results from this study were very limited, they did show that a large variability in life was possible at a given load. Two tests, both at $F_{max} = 24$ kN, had over an order of magnitude difference in life.

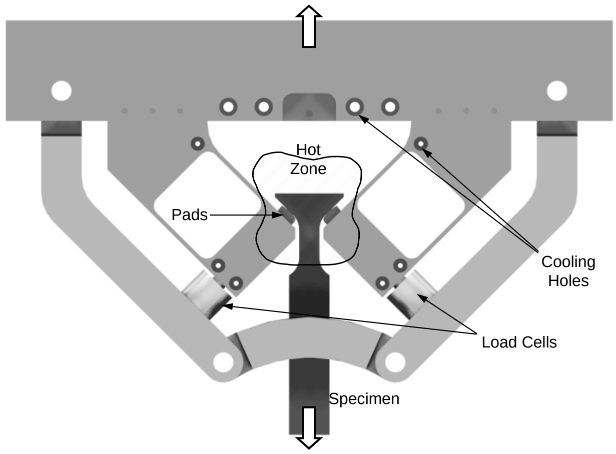


Figure 6. Drawing of the elevated temperature dovetail fretting fatigue fixture

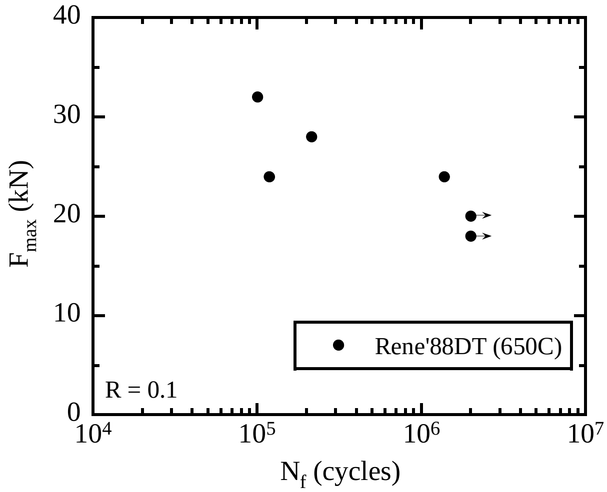


Figure 7. Q/P load history for a run-out Rene'88DT specimen

F. Crack Growth in Spin Pit Environments

Many turbine engine components are tested in spin pits to assess their durability and to validate the life prediction methods used in their design[22]. These spin tests are typically conducted in pits evacuated to a moderate vacuum level to minimize the aerodynamic heating (and reduce the power consumption) of blades disks. However, the effect of the partial vacuum is seldom taken into account in the assessment of the design methodology, and there is a dearth of experimental data regarding the influence of this environment. Tests were conducted at two intermediate vacuum levels to assess the influence of a spin pit environment on the crack growth behavior of powder metallurgy IN100 and conventionally wrought Waspaloy[23]. The test conditions and loading rates were designed to match particular spin pot tests. Under the partial vacuum conditions, a reduction in crack growth rate was observed in IN100 for continuous cycling, while an *anomalous* increase in fatigue crack growth rate was apparent at low K_{max} levels for cycling that included a hold period at maximum load. Under the same partial vacuum conditions, Waspaloy exhibited an *anomalous* increase in crack growth rate for both continuous cycling and cycling that included a hold period. These results are shown in Fig. 8 for the two materials in terms of an environmental factor. This puzzling behavior is not fully understood at this

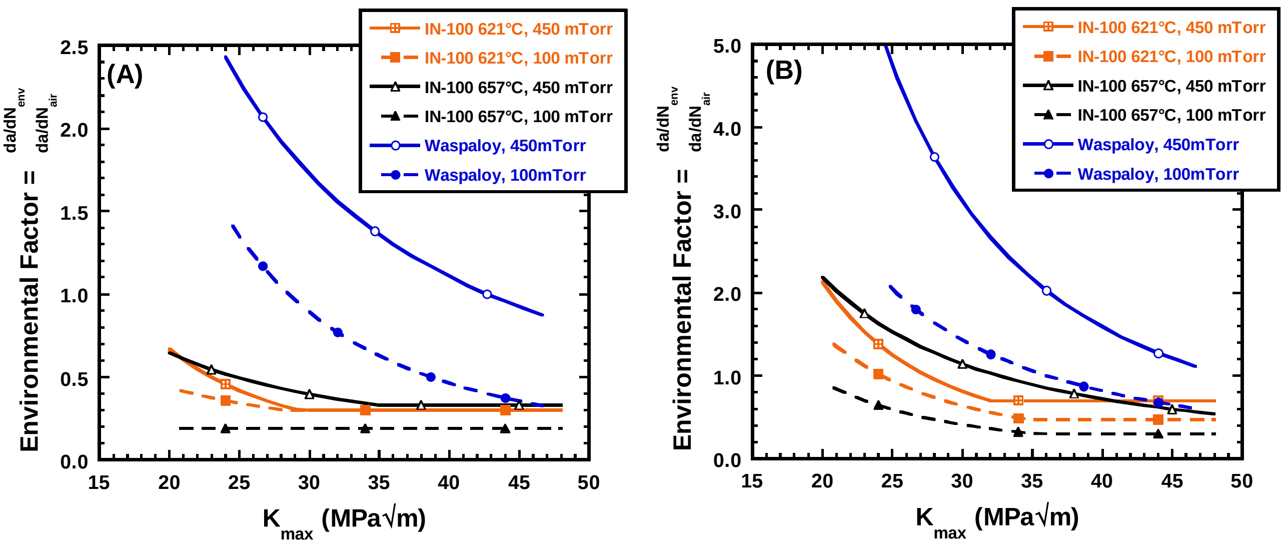


Figure 8. The environmental factor (EF= da/dNenvironemnt / da/dNair) as a function of Kmax for IN-100 and Waspaloy (650°C test temperature); a) continuous cycling (0.033Hz for IN-100/0.0167Hz for Waspaloy), and b) with 60s hold times (note the different scales).

time. It may be due to changes in protective oxide scale formation or differential pumping rates of the embrittling species at the different partial pressures. Careful work is necessary to understand the complex chemical and mechanical interactions at a growing crack tip. However, while the cause(s) of this behavior is not understood, it clearly points to a potential error in validating life methods using spin articles.

G. Crack Growth Under Variable Amplitude High Cycle Fatigue (HCF) Loading

Within the Fan/Compressor Airfoil (FCA) Module of the ESP program, tremendous progress was made in demonstrating the capability to detect and monitor fatigue crack propagation within airfoils through the integrated use of sensor information and advanced component structural analyses.[24] Of particular interest in developing this capability were a method to predict and a means to validate fatigue crack growth behavior under the variable amplitude, high cycle fatigue (HCF) loading experienced in airfoils during brief sweeps through resonant modes during throttle transients.[25] During these brief resonant excitations, isolated regions of an airfoil experience a surge of progressively increasing then decreasing stress amplitude. AFRL developed a set of experiments to apply a variable amplitude loading profile, representative of a typical sweep through resonance experienced in airfoils, to both long and small crack growth specimens. The loading profile, shown in Figure 9, was applied to compact tension, C(T), and cylindrical fatigue specimens of Ti-6Al-4V at room temperature and a frequency of 20 Hz[26, 27]. Crack growth rates were predicted using a cycle-by-cycle analysis, whereby the contribution to growth from each individual fatigue cycle was determined using AFGROW, a standard fatigue crack growth software tool, and load interaction effects were considered negligible. Further details on the experimental method and prediction approach can be found in references.[26,27] Figure 10 shows that the predictions from the cycle-by-cycle analysis are in very close agreement with experimental observations. Notably in Figure 2b, it is seen that while the prediction provides an excellent characterization of the behavior of the most dominant small crack, three additional small cracks were monitored that demonstrated slower initial growth rates. This underscores the importance of extending our understanding of the significant scatter observed in small fatigue crack growth behavior and developing improved mechanism-driven, probabilistic modeling for this regime.

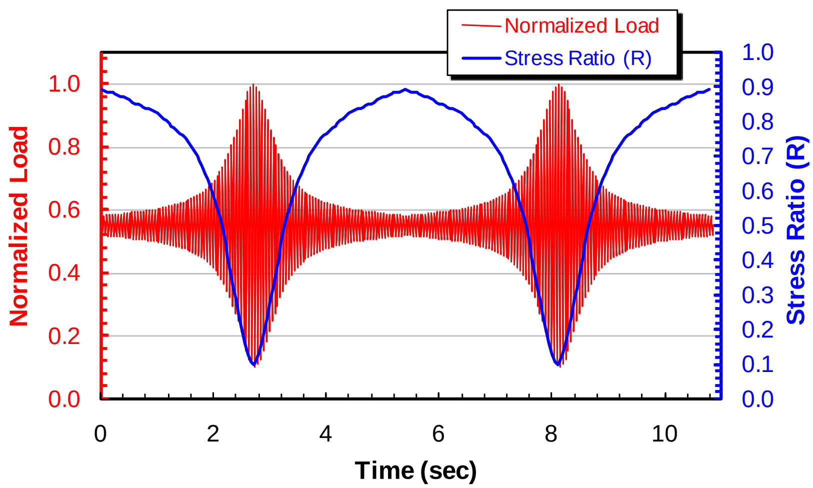
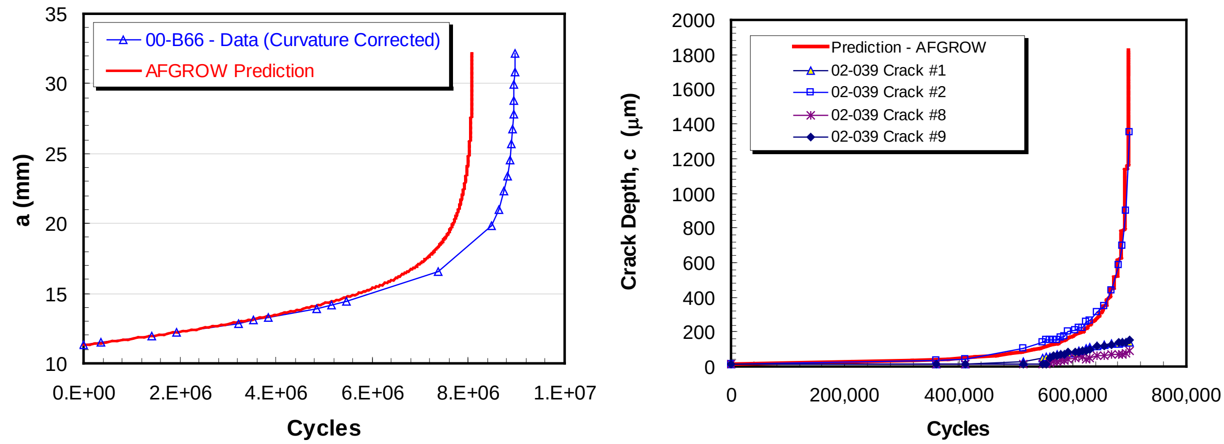


Figure 9. Loading profile applied to laboratory fatigue specimens, representative of variable amplitude loading experience in airfoils during throttle transients.



(a) **(b)**

Figure 10. Fatigue crack growth data and predictions for (a) long crack and (b) small cracks tested under the loading profile shown in Figure 1.

III. Avenues for Validation and Application

Two primary avenues for further development, maturation, and transition of the results reported here are (i) through improvements to methods of prognosis of currently fielded systems and (ii) through the integrated design and certification of materials and structures for future systems. Both avenues of pursuit, however, must be accompanied by approaches to validate the models and tools that will be used, and the current fleets represent a remarkable, and largely untapped, source of extremely important information for feedback. We believe that, through careful, selective and systematic observation of detailed damage sites, today's systems can be an extremely valuable proving ground for the methods of today and tomorrow. Validation of improved models against the historical behavior of today's fielded systems provides richness of the results of actual use over many years and provides the opportunity to confirm or identify routine and rare mechanisms and events resulting from a lifetime of service. Therefore we are pursuing a program of advance validation science to explore and develop efficient methods to extract the "needle in a haystack" information through the examination of retired components. This effort begins with examination of historical data from nondestructive evaluation of components when they are returned to the depot for routine service. These extraction results are to be mined to identify the components and locations most likely to exhibit early damage. Based on these examinations, the retiring components that are most likely to contain significant levels of subcritical damage can be identified, and the identified damage locations can be captured for further nondestructive and destructive examination to characterize the actual damage. The results of this characterization of field service damage then serve as a set of benchmark data for comparison with model prediction of mechanisms and damage progression for use with both current and future materials.

As systems age and approach their design lifetime, questions arise regarding the possible process and risks if the systems were to be used beyond their original design lifetimes. These are very natural questions, given economic pressures and the fact that much new science and technology has since been developed or improved since the now aging systems were manufactured. Through the types of activities reported in this paper, we are exploring options for reducing uncertainties in tools for design, certification, and prognosis of materials and structures. We are examining a full suite of science and technology that could enable the safe, reliable, and cost effective extension of useful lifetime and provide improved methods to calculate risk and assure safety. To this end, the DARPA Engine System Prognosis program has developed and demonstrated many new capabilities that are available for implementation. The supporting work reported here provides less mature, but no less significant, opportunities for further improvement in predictive accuracy and reduction in uncertainly. Key areas of opportunity appear to exist in terms of definition and modeling of mechanisms. The implementation of engineering methods for probabilistic modeling will provide a critical opportunity for the insertion and validation of new models that enable condition base management plus (CBM+), where plus stands for prognosis. Given the common needs of the military and commercial engine operators, the opportunities for synergy between these two sectors is immense and very timely.

Understanding the importance of alloy characteristics on the behavior of the material is also beginning to mature, based on this body of research. Such understanding is critical for the emerging field known as Integrated Computational Materials Engineering (ICME).[28] The central goal of ICME is to link materials, manufacturing processes, and component design using an integrated computational and engineering framework. The goal is to enable material selection and microstructural optimization using integrated, mechanistically accurate, multi-scale computational models, much like structural design is now routinely accomplished through the application of relatively mature finite element methods. The body of work in this study has resulted in, for example, a new understanding of the influence of microstructure characteristics on life-limiting fatigue. Pores, nonmetallic inclusions, occasional large grains, and micro-texture all affect the fatigue behavior of a material in unique ways. As the mechanism basis of the models matures, this understanding can be reversed in the ICME framework to prescribe optimized material characteristics or processes to meet certain life or loading requirements. In additional to materials microstructural features, ICME should incorporate effects of induced surface residual stress, process-induced bulk residual stresses, the influence of both the environmental attack and local contact stresses, and capabilities and limitations of the nondestructive evaluation tools, which can certify initial material quality and quantify service induced changes in microstructure or capability. The efforts to better assess the impact of usage on damage accumulation via "benchmarking" of components will provide real-world validation of the accuracy of the IMCE approach to predict the level of damage and the damage mode. We believe that through ICME methods, there is immense promise for this body of research to change the way new systems are designed and managed throughout their lifetimes.

IV. Conclusion

New understanding has been developed in a number of area regarding key factors that limit the design lifetime in advanced propulsion materials. These factors include understanding inherent material variability, effects of surface and bulk residual stresses, capabilities of advanced nondestructive inspection, fretting fatigue, environmental effects, and variable amplitude high cycle fatigue. Through the integration of the findings into a probabilistic framework, it appears that significant improvements are possible in terms of the prediction of service lifetime of today's materials and components and the optimized design of future materials and structures.

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